# Estimating Biophysical and Biochemical Properties over Heterogeneous Vegetation Canopies

# Radiative Transfer Modeling in Forest Canopies Based on Imaging Spectrometry and LIDAR

**Dissertation**

**zur**

**Erlangung der naturwissenschaftlichen Doktorwürde**
**(Dr. sc. nat.)**

**vorgelegt der**

**Mathematischen-naturwissenschaftlichen Fakultät**

**der**

**Universität Zürich**

**von**

**Benjamin Kötz**

**aus**

**Deutschland**

**Promotionskomitee**
**Prof. Dr. Klaus I. Itten (Vorsitz)**
**Dr. Britta Allgöwer**
**Dr. Mathias Kneubühler**
**Prof. Dr. Michael Schaepman**

**Zürich, 2006**

## Abstract

Vegetation controls important ecosystem processes responsible for energy and mass exchanges within the terrestrial biosphere. A comprehensive characterization of the vegetation canopy is thus required to monitor the heterogeneous and dynamic terrestrial biosphere.

Although Earth Observation provides detailed measurements of the Earth surface, it has been a challenge to produce reliable data sets of the Earth vegetation condition in its spatial distribution and change over time. Relative to the heterogeneous and three-dimensional nature of vegetation the generally available amount of independent Earth Observation measurements is limited. The problem of deriving vegetation characteristics from Earth Observation becomes consequently underdetermined. For an improved retrieval of vegetation characteristics the number of independent information sources needs to be increased.

However, detailed measurements of the Earth Observation systems imaging spectrometry and LIDAR provide such independent information. The information dimensions observed by the two sensor systems contain data relevant to different aspects for a comprehensive characterization of vegetation canopies. The information dimension observed by LIDAR provides direct measurements of the vertical canopy structure including the canopy height. Whereas, the spectral information dimension provided by imaging spectrometers contains information about biophysical as well as biochemical canopy properties.

The presented dissertation focuses on the combined exploitation of the independent Earth Observation measurements of imaging spectrometry and LIDAR based on radiative transfer modeling. The approach of radiative transfer modeling explicitly describes the relationship between the remotely sensed signal and vegetation characteristics. A Radiative Transfer Model (RTM) considers the incident radiation, sensor specifications and physical processes that govern the radiative transfer within the canopy. Two such physically based RTM are employed to separately describe the signals of an imaging spectrometer and a large footprint LIDAR. The combined inversion of these RTM's presents an efficient methodology for a synergistic exploitation of the independent information dimension obtained by the two Earth Observations systems.

The developed methodology ensures a retrieval algorithm of increased robustness, but also provides an enhanced vegetation canopy characterization. Results present reliable and quantitative estimates of canopy characteristics including the horizontal and vertical canopy structure as well as the foliage biochemistry over coniferous forest stands. The dissertation shows thus the potential of independent information dimensions of Earth Observation and RTM inversion for the retrieval of quantitative vegetation characteristics.

## Zusammenfassung

Vegetation kontrolliert wichtige Ecosystem-Prozesse, die für den Austausch von Energie und Masse innerhalb der terrestrischen Biosphäre verantwortlich sind. Eine umfassende Beschreibung der Vegetationsbestände ist folglich notwendig, um die heterogene und dynamische terrestrische Biosphäre systematisch zu beobachten.

Obwohl die fernerkundliche Erdbeobachtung detaillierte Messungen von der Erdoberfläche liefert, sind verlässliche Datensätze über den Vegetationszustand der Erde in seiner räumlichen Verteilung und zeitlichen Veränderung nach wie vor eine Herausforderung. Im Vergleich zu der heterogenen und drei-dimensionalen Beschaffenheit der Vegetation sind die generell verfügbaren unabhängigen Messungen der Erdbeobachtung limitiert. Die Ableitung der Vegetationseigenschaften von Erdbeobachtungen wird so zu einem unterbestimmten System. Für eine verbesserte Ableitung von Vegetationseigenschaften muss die Anzahl von unabhängigen Informationsquellen erhöht werden.

Die detaillierten Messungen der beiden Erdbeobachtungssysteme Bildspektrometrie und LIDAR liefern solche unabhängigen Informationen. Die Informationsdimensionen aufgenommen durch die zwei Sensorsysteme enthalten relevante Daten für unterschiedliche Aspekte einer umfassenden Vegetationsbeschreibung. Die Informationsdimension eines LIDAR (engl. LIght Detection And Ranging) liefert direkte Messungen der vertikalen Bestandesstruktur einschließlich der Bestandeshöhe. Die spektrale Informationsdimension der Bildspektrometrie enthält dagegen Informationen über die biophysikalischen und biochemischen Bestandeseigenschaften.

Die vorliegende Dissertation konzentriert sich auf die kombinierte Auswertung der unabhängigen Dimensionen der Erdbeobachtung durch Bildspektrometrie und LIDAR basierend auf Strahlungstransfermodellierung. Der Ansatz der Strahlungstransfermodellierung beschreibt explizit den Zusammenhang zwischen dem Fernerkundungssignal und Vegetationseigenschaften. Ein Strahlungstransfermodell (RTM, engl. Radiative Transfer Model) berücksichtigt die einfallende Strahlung, Sensorspezifikationen und die physikalischen Prozesse, welche den Strahlungstransfer innerhalb eines Bestandes beherrschen. Zwei solcher physikalisch basierten RTM werden eingesetzt, um die Signale eines Bildspektrometers und eines large footprint LIDAR (LIDAR mit weiter Beleuchtungszone) separat zu beschreiben. Die kombinierte Invertierung dieser zwei RTM führte zu einer synergetischen Auswertung der unabhängigen Informationsdimensionen der beiden Erdbeobachtungssysteme.

Die entwickelte Methode bietet nicht nur einen Algorithmus von höherer Verlässlichkeit, sondern liefert auch eine erweiterte Beschreibung des Vegetationsbestandes. Zuverlässige und quantitative Schätzungen von Bestandeseigenschaften wurden erreicht, die sowohl die horizontale und vertikale Bestandesstruktur als auch die Biochemie der Belaubung eines Nadelwaldes umfassten. Die Resultate des vorgeschlagenen Ansatzes zeigt das Potenzial von unabhängigen Informationsdimensionen der Erdbeobachtung und von Strahlungstransfermodel-Invertierung für die Ableitung von quantitativen Vegetationseigenschaften.

## Table of Contents


**Abstract** **I**
**Zusammenfassung** **II**
**Table of Contents** **III**
**List of Figures** **VI**
**List of Tables** **VIII**
**List of Abbreviations** **IX**
**List of Symbols** **XI**

PART A: SCIENTIFIC SETTING 1

**Introduction: Challenges in Monitoring of Vegetation** **2**
The international policy context 2
Requirements of Earth Observations over vegetated land surface 3
Challenges and limitations of Earth Observation over vegetated land surface 4
**Dimensions of Earth Observation for vegetation characterization** **6**
Spatial information dimension 6
Spectral information dimension 7
Directional information dimension 7
Temporal information dimension 8
**Radiative Transfer within a vegetation canopy** **9**
Leaf level 9
Canopy level 9
Radiative transfer modeling 10
**Rationale of Dissertation** **12**
Motivation 12
Objectives 13
Structure 14
Part A: Scientific Setting 14
Part B: Publications 14
Part C: Synopsis 14
Practical context 14
**References** **16**

PART B: PUBLICATIONS OF THE DISSERTATION 31

**Radiative transfer modeling within a heterogeneous canopy for estimation of forest fire fuel properties** **32**
**Abstract** **33**
**1. Introduction** **33**
1.1. Background: fuel properties and remote sensing 34
**2. Study site and data description** **34**
2.1. Sampling scheme 35
2.2. Canopy structure 35
2.3. Biochemistry of the canopy 35
2.4. Spectral properties of canopy components 37
2.5. Imaging Spectrometry data 37

**3. Radiative transfer modeling for canopy parameter estimation** **38**
3.1. RTM parameterization and error propagation 38
3.2. Inversion of GeoSAIL 39
**4. Results and discussion** **40**
**5. Conclusions** **42**
**Acknowledgements** **42**
**References** **43**

**Inversion of a LIDAR Waveform Model for Forest biophysical Parameter Estimation** **46**
**I. Introduction** **47**
**II. LIDAR Waveform Model** **47**
**III. Data** **48**
A. Synthetic Datatset 48
B. Swiss National Park Dataset 48
**IV. Inversion of Waveform Model** **49**
**V. Results and Discussion** **49**
A. Synthetic Dataset 50
B. Swiss National Park Dataset 50
**VI. Conclusion** **50**
**Acknowledgment** **51**
**References** **51**

**Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization** **52**
**Abstract** **53**
**Introduction** **53**
**Radiative Transfer Models** **55**
GeoSAIL 55
LIDAR Waveform model 55
**Data: Generation of synthetic data set** **56**
Forest growth modeling: ZELIG simulations 57
Remote sensing signatures 58
Spectral canopy reflectance 58
LIDAR waveform 59
**Methods: RTM Inversion based on Look Up Tables (LUT)** **59**
Generation of the LUT 60
Selection of the solution 60
Exploiting waveform information: definition of prior information 61
Exploiting combined spectral and waveform information 61
**Results and discussion: Evaluation of RTM coupling strategy** **62**
**Conclusions** **64**
**References** **65**

PART C: SYNOPSIS 71

Main findings and progress 72
Conclusions 75
Outlook 76
References 77

APPENDIX 79

Acknowledgements 80
Curriculum Vitae 81
Personal Bibliography 82

## List of Figures


**Scientific Setting**

| | | |
|---|---|---|
| Figure 1 | Information flow from Earth Observation to the information products relevant for decision-making using radiative transfer models (RTM) and land surface process models (LSPM) (based on Verstraete et al., 1996). | 5 |
| Figure 2 | Conceptual scheme of radiative transfer modeling in its forward and inverse mode. | 11 |

**First Publication**

| | | |
|---|---|---|
| Figure 1 | Airborne imaging spectrometer data over the four core test sites (yellow crosses indicate the sampling points). The image composite represents geocoded and atmospherically corrected data of the spectrometer ROSIS in spatial resolution of 1 m resolving the heterogeneity of the observed forest. The long-term Forest Ecosystem Research site of WSL where forest stand characteristics are acquired is indicated by the rectangle. | 36 |
| Figure 2 | Reflectance of the canopy components understory and bark representing the spectral properties of the background and the woody parts necessary for the radiative transfer parameterization. Error bars indicate the variability (one standard deviation, number of measurements: 35 understory spectra, 10 bark spectra) of the measurements. | 37 |
| Figure 3 | Comparison of simulated canopy reflectance by GeoSAIL and FLIGHT for the core test site LWF1, including their respective uncertainties (δGeoSAIL, δFLIGHT). The root-mean-square error over the whole wavelength range amounted to 0.9% reflectance. | 39 |
| Figure 4 | Simulated (GeoSAIL) and measured canopy reflectance of the four core test sites. Error bars represent the uncertainties of the RTM approach (solid grey) and of the DAIS measurements including errors of radiometric correction and spatial variability (black squares with error bars). | 40 |
| Figure 5 | Performance of model inversion: estimates and measurements of canopy parameters are presented; error bars represent the uncertainties related to the ground measurements and model inversion, respectively (LAI x Cw, canopy water content; LAI x Cdry, canopy dry matter content). | 41 |

**Second Publication**


| | | |
|---|---|---|
| Figure 1 | Example of a 3-D forest stand representation for waveform simulations, parameterization: 60 trees, maximum tree height: 15 m; crown length: 4 m; crown width: 3 m; crown shape: hemi-ellipsoid; LAI: 2.5; G-factor: 0.5; leaf reflectance: 0.215; background reflectance: 0.152; footprint: 25 m. | 48 |
| Figure 2 | Performance of the model inversion for the synthetic data set, circles represent the median of possible solutions and error bars represent the uncertainties related to the model inversion (standard deviation of possible solutions). | 49 |
| Figure 3 | Performance of the model inversion for the SNP data set, circles represent the median of possible solutions and error bars represent the uncertainties related to the field measurements and model inversion (standard deviation of possible solutions). | 50 |


**Third Publication**


| | | |
|---|---|---|
| Figure 1 | Simulated remote sensing signatures for the large footprint LIDAR LVIS (Blair et al. 1999) and the imaging spectrometer APEX APEX (Nieke et al., 2004) (measurement uncertainties indicated by red error bars) over forest stands generated by the forest growth model ZELIG (stand ages: 5, 50, 100 years, soil type ADAMS) | 56 |
| Figure 2 | Vegetation parameter estimates describing the vertical and horizontal canopy structure retrieved by the inversion of the LIDAR waveform RTM. Results describe forest stands generated by ZELIG over the soil type ADAMS (n=390 forest stands). Error bars represent the uncertainty of the model inversion. | 63 |
| Figure 3 | Estimates of biophysical and biochemical parameters retrieved based solely on the spectral information content (Fig. 3a) as well as on the coupled RTM inversion (Fig. 3b). Results describe forest stands generated by ZELIG over the soil type ADAMS (n=390 forest stands). Error bars represent the uncertainty of the model inversion. | 64 |

## List of Tables


**First Publication**

| | | |
|---|---|---|
| Table 1 | Field observations of canopy variables including relative measurement errors relevant for the canopy parameterization of the RTMs PROSPECT, GeoSAIL and FLIGHT | 36 |
| Table 2 | Specific ranges for each parameter describing the space of canopy realizations for the generation of the lookup table | 40 |

**Second Publication**

| | | |
|---|---|---|
| Table 1 | Instrument Specifications for LVIS waveform emulation, adapted from [18] | 51 |
| Table 2 | Parameter ranges and distribution describing the generation of the LUT. Additional parameters were fixed to default or field measurement values: foliage reflectance (l: 1560 nm): 0.215, background reflectance (l: 1560 nm): 0.152, crown shape: hemi-ellipsoid, G-factor: 0.5 and Tree number: 60. | 51 |

**Third Publication**

| | | |
|---|---|---|
| Table 1 | Parameter ranges describing the generation of the synthetic data set as well as the LUT for the subsequent RTM inversion. Additional parameters were fixed to model default or field measurement values: GeoSAIL parameterization: wood fraction = 0.09%, crown height width ratio = 7.8, crown shape = cone, spectral properties of woody canopy elements and understory; Waveform model parameterization: foliage reflectance (l: 1560 nm) = 0.215, background reflectance (l: 1560 nm) = 0.152, crown shape: hemi-ellipsoid, G-factor= 0.5, tree number = 60 (for the LUT generation) | 57 |
| Table 2 | Specification of the planned imaging spectrometer APEX (Nieke et al., 2004) | 59 |
| Table 3 | Instrument Specifications for LVIS waveform emulation, adapted from Blair & Hofton, 1999 | 59 |
| Table 4 | Retrieval performances for the respective canopy parameters based on the LIDAR waveform information and based on the combined spectral and waveform information. Overall performance as well as separate performaces for ten different soil types are quantified as RMSE and R2 between reference and estimated parameters. | 62 |

## List of Abbreviations

| | |
|---|---|
| ALOS | Advanced Land Observing Satellite (JAXA) |
| APEX | Airborne Prism Experiment |
| Aqua | NASA EOS platform carrying six sensors, launched in May 2002 |
| ASD | Analytical Spectral Devices |
| CBD | Convention on Biological Diversity |
| CHRIS | Compact High Resolution Imaging Spectrometer (ESA) |
| DAIS | Digital Airborne Imaging Spectrometer (DLR) |
| DBH | Tree Diameter at Breast Height |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) |
| EC | European Community |
| EOS | Earth Observation System |
| ESA | European Space Agency |
| EWT | Equivalent Water Thickness |
| FAPAR | Fraction of Absorbed Photosynthetic Active Radiation |
| FARSITE | Fire ARea Simulator |
| fcover | fractional cover |
| FLIGHT | Forest LIGHT interaction model |
| FMC | Fuel Moisture Content |
| GeoSAIL | Geometric extended SAIL model |
| GEOSS | Global Earth Observation System of Systems |
| GLAS | Geoscience Laser Altimeter System (NASA) |
| GMES | Global Monitoring of Environment and Security |
| IceSAT | Ice, Cloud, and land Elevation Satellite (NASA) |
| IEEE | Institute of Electric and Electronics Engineers |
| INRA | Institute National de la Recherche Agronomique |
| IPCC | Intergovernmental Panel of Climate Change |
| JAXA | Japan Aerospace eXploration Agency |
| LAD | Leaf Angle Distribution |
| LAI | Leaf Area Index |
| LIDAR | LIght Detection And Ranging |
| LSPM | Land Surface Process Model |
| LUT | Look-Up Table |
| LVIS | Laser Vegetation Imaging Sensor (NASA) |
| MIR | Middle InfraRed |
| MISR | Multiangle Imaging SpectroRadiometer (NASA) |
| MODIS | MODerate resolution Imaging Spectrometer (NASA) |

| | |
|---|---|
| NASA | National Aeronautics and Space Administration |
| NEF | Northern Experimental Forests |
| NIR | Near InfraRed |
| PALSAR | Phased Array type L-band Synthetic Aperture Radar (JAXA) |
| Proba | Project for On-Board Autonomy platform (ESA) |
| PROSPECT | leaf optical PROperties SPECTra model |
| $R^2$ | correlation coefficient |
| RADAR | RAdio Detection And Ranging |
| RAMI | Radiation Transfer Model Intercomparison |
| RMSE | Root Mean Square Error |
| ROSIS | Reflective Optics System Imaging Spectrometer (DLR) |
| RPV | Rahman-Pinty-Verstraete model |
| RTM | Raditative Transfer Model |
| SAIL | Scattering from Arbitrarily Inclined Leaves |
| SNP | Swiss National Park |
| SNR | Signal to Noise Ratio |
| SPREAD | Forest fire SPREAD and Mitigation, EC project |
| SWIR | ShortWave InfraRed |
| TERRA | NASA EOS platform carrying five sensors, launched in April 1999 |
| UNCED | United Nations Conference on Environment and Development |
| UNFCC | United Nations Framework Convention on Climate Change |
| VALERI | VALidation of Land European Remote sensing Instruments |
| VIS | VISible part of the electromagnetic spectrum |
| ZELIG | Forest growth model (Urban 1990) |
| SAIL | Scattering from Arbitrarily Inclined Leaves |
| SNP | Swiss National Park |

## List of Symbols

| | | |
|---|---|---|
| $\rho$ | Reflectance | [dimensionless] |
| $\Theta$ | Zenith angle | [deg], [rad] |
| $\Psi$ | Azimuth angle | [deg], [rad] |
| $\lambda$ | Wavelength | [nm] |
| $\omega$ | Relative signal of LIDAR waveform | [dimensionless] |
| $\sigma_p$ | Along-beam laser intensity half-width | [m] |
| $\sigma_f$ | Across-beam laser intensity half-width | [m] |
| $\chi^2$ | Merit function | |
| Cab | Foliage chlorophyll content | [$\mu g/cm^2$] |
| Cw | Foliage water content | [$mg/cm^2$] |
| Cdry | Foliage dry matter | [$mg/cm^2$] |
| N | Foliage mesophyll structure index | [dimensionless] |
| LAI | Leaf Area Index | [dimensionless] |
| fcover | Fractional canopy cover | [%] |
| Tree_z | Maximal tree height | [m] |
| C_ext | Vertical crown extension | [m] |

# PART A: SCIENTIFIC SETTING

## Introduction: Challenges in Monitoring of Vegetation

Today a large number of remote sensing platforms observe the Earth's vegetation at wavelengths ranging from the visible to microwave domain based on passive or active systems, at spatial resolutions ranging from sub-meter to kilometers and at very variable temporal frequencies. In this work the term Earth Observation will be used for the acquisition of remotely sensed data from air- or spaceborne sensor systems. Earth Observation measurements serve diverse applications related to monitoring of vegetation including local precision farming, global carbon stock modeling and mitigation of natural hazards such as forest fires (Chuvieco 2003; Inoue 2003; Rosenqvist et al. 2003a). In the following the significance and requirements of Earth Observation over vegetated land surfaces are addressed for scientific and operational issues. Further, the challenges as well as the limitations of Earth Observation for monitoring of the essential parameters describing the vegetation are discussed.

### The international policy context

The regional to global importance to assess the characteristics of the vegetated land surface over space and time by Earth Observation is laid out in a series of political charters and treaties.

As stated by the Intergovernmental Panel of Climate Change (IPCC) the anthropogenic emissions of greenhouse gases have already started to impact the climate of the Earth (IPCC 2001). The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), established as the institutional framework governing the issue of climate change, sets therefore quantified and legally binding targets to limit or reduce the greenhouse emissions to 1990 levels (Steffen et al. 1998). The Kyoto Protocol also accounts for sinks of carbon emissions associated to vegetation growth and expansion. Monitoring of processes such as land use change, in specific afforestration, reforestration and deforestration, is in this context of significant importance (Schulze et al. 2002).

Biological diversity is another global issue ranking high on the agenda of global environmental governance. Biodiversity, in many respects essential to life on Earth and for human well being, is already being lost more rapidly in the past 50 years than at any time in human history. Projections and scenarios indicate that these rates will continue, or accelerate, in the future (DIVERSITAS 2002; IPCC 2002). Against this background a number of international policies have been set up for the conservation of natural resources including vegetation. Among the many political measures that have been established to address this issue, the Convention on Biological Diversity (CBD), also drawn up at the 1992 United Nations Conference on Environment and Development (UNCED), certainly constitutes the most important institutional framework. Further relevant global efforts resemble in the Convention to Combat Desertification and the Ramsar Convention on Wetlands (UN 1971).

Another example of the importance of Earth Observation to international environmental governance is given by the actions for an integrated natural disaster management requested in the Plan of Implementation of the World Summit on Sustainable Development, held in 2002 at Johannesburg (UN 2002). In support of such requirements the international charter "Space and Disasters" has been founded and signed by a number of national space agencies and the United Nations. The charter "Space and Disasters" provides a system for the acquisition and delivery of Earth Observation data in response to natural or man-made disasters. For example, monitoring of vegetation plays a major role in the context of natural hazards, since it acts as fuel for the propagation of wildland fires (Carlson and Burgan

2003).
In support of the implementation and surveillance of these policies the environmental state and changes of the Earth vegetation need to be assessed and monitored. The recent European initiative Global Monitoring of Environment and Security (GMES) aims at providing the operational capacity for the provision of data and services necessary for such a demand (Brachet 2004). Furthermore, the Global Earth Observation System of Systems (GEOSS) has been established to organize the efforts of different nations on the international level for providing spatial and temporal consistent observations of the environment (GEO 2005).

### Requirements of Earth Observations over vegetated land surface

Earth Observation in general is an excellent tool for monitoring the environmental state of a vegetation canopy over space and time. It provides spatially continuous and temporally frequent information products over extended areas. However, a number of requirements have to be met to produce reliable Earth Observation information based products.
The basic requirement for an operational retrieval of bio- and geophysical land surface parameters from remote sensing data is a temporal and spatial consistent data basis (Coppin et al. 2004; Rosenqvist et al. 2003b; Townshend et al. 1994). Depending on the objectives of a chosen approach, not only the spatial extent and coverage, the temporal repetition frequency but also accurate timing, sensor consistency and long-term continuity have to be considered (Rosenqvist et al. 2003b; van Leeuwen et al. 2006). These requirements demand a systematic observation strategy as well as thorough pre-processing of the remote sensing data set including radiometric calibration, radiometric and geometric correction, compensation of disturbing effects and temporal-spatial co-positioning (Beisl 2001; Duggin and Robinove 1990; Itten and Meyer 1993; Richter and Schläpfer 2002; Schiefer et al. 2006; Schläpfer and Richter 2002).
The different thematic fields, where Earth Observation of vegetation is of significant importance, require a wide range of information products. For applications in the agricultural sector specific information regarding the health, maturity and quantity of crops is demanded in very timely manner and at high spatial resolution (Inoue 2003; Moran et al. 2003). Biophysical canopy characteristics derived from remote sensing data such as the Leaf Area Index (LAI), leaf chlorophyll and moisture content can be interpreted for maps of nutrition status and yield predictions, important for critical farm management decisions (Baret et al. 2000; Doraiswamy et al. 2003).
The Earth Observations requirements for assessing ecosystem functioning are defined by the responses of ecosystems to external changes on different spatial and temporal scales (Asner et al. 1998; Thornton et al. 2002). The consistency of data products will be the challenge here for Earth Observation. Only consistent Earth Observation data can provide long time series and generally accepted baselines of vegetation conditions, essential for research of ecosystem functioning. Land surface parameterizations of the soil-vegetation-atmosphere-transfer based on actual and archived remote sensing data have been already used to validate and initialize ecosystem models ranging from regional to global scales (Cramer et al. 1999; Sellers et al. 1997; Sellers et al. 1996). Relevant land surface parameters inferable by optical Earth Observation include the distribution of plant functional types, fractional vegetation cover, LAI, Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), surface albedo and roughness length (Ranson et al. 2001; Rast 2004; Schaepman et al. 2004; Ustin et al. 2004; Widlowski et al. 2004).
Earth Observations requirements of vegetation in the context of natural hazards are often driven by their use for detection, mitigation and management of wildland fires (Allgöwer et al. 2003; Carlson and Burgan 2003; Csiszar et al. 2005; Justice et al. 2003). Fuel properties

such as fuel load, canopy structure, fraction of dead biomass and fuel moisture are essential for the assessment of fire risk and the prediction of fire behavior (Chuvieco et al. 2002; Lynham et al. 2002). Fire behavior models based on spatial distribution of fuel properties can predict the probability of fire initialization and characteristics of the fire behavior such as rate of spread, intensity, duration and extension of the burning. The main challenge in the operational use of remote sensing data in fire danger systems is the high temporal frequency and near-real-time requirement for fire risk assessment as well as the high resolution in horizontal and vertical dimension needed for fire behavior prediction and management (Andrews and Queen 2001; Keane et al. 2001; Leblon 2005). The detection of vegetation cover by Earth Observation is also of indirect use for the risk and impact assessment of natural hazard such as landslides and flooding (Ostir et al. 2003; Tralli et al. 2005).
All of these applications require reproducible products with explicit thematic or quantitative information content. The development and implementation of algorithms for Earth Observation products, which fulfill these prerequisites, require a thorough understanding of the general physical processes affecting the signal of Earth Observation.

#### Challenges and limitations of Earth Observation over vegetated land surface

Earth Observation is basically the measurement and interpretation of spatially distributed radiation fluxes reflected or emitted from the Earth surface. The measured radiation fluxes are driven by radiative transfer processes, such as scattering, absorption and emission, intrinsically related to the properties of the observed surface. However, the variables controlling the radiative transfer and thus also remotely sensed data are not necessarily directly related to the surface properties of ultimate interest (Verstraete et al. 1996). The main challenge in Earth Observation is consequently to establish - in spite of this fact - a solid relationship between the diverse measurements of radiation fluxes and application driven information products. Due to the indirect and in the case of vegetation mostly underdetermined character of this relationship, interpretation of Earth Observation data should thus rely on as many independent observations as possible. In addition the knowledge of the involved physical and biological processes needs to be considered in the interpretation of remote sensing data.
The geometric and physical properties of the canopy control the radiative transfer of the incident radiation and are thus important factors for Earth Observation of vegetation. The geometric properties of a vegetation canopy can be described by the density, distribution and size of canopy elements in a three dimensional space (Goel and Thompson 2000). In the case of a forest also the distribution of trees and the crown geometry have to be considered (Chen et al. 2000; Gerard and North 1997). As physical properties the reflectance and transmittance of the foliage, branches and background are of importance (Baret et al. 1994; Gao et al. 2000). It can be thus concluded that a vegetation canopy, being a three dimensional, semi-transparent and heterogeneous medium, is controlled by numerous radiative state variables.
Considering the limited amount of measurements generally provided by Earth Observation and the high number of open variables, the problem of estimating vegetation properties based on remote sensing data is underdetermined (Combal et al. 2003; Kimes et al. 2000; Wang et al. 2001). A reliable retrieval is thus only possible if additional assumptions, constraints or further independent observations are introduced (Verstraete et al. 1996). Assumptions and constraints are often used to simplify the problem, but are also limiting the retrieval in its transferability since they are generally only applicable for a specific problem. The interpretation of empirically based algorithms, such as vegetation indices, are

impacted by these limitations. Due to their empirical nature, they have to be calibrated for certain vegetation types and environmental conditions to account for influences caused by the background signal and canopy architecture (Baret and Guyot 1991).

Earth Observation can only provide information on vegetation properties, which have a direct impact on and are sensitive to the measured radiation fluxes (figure 1). Consequently the explicit retrieval of vegetation properties based on remote sensing is limited to variables directly involved in the radiative transfer within the canopy, the radiative state variables (figure 1) (Verstraete et al. 1996). Estimations of higher information product levels, such as final yield or net primary production, must therefore rely on further interpretations of the retrieved variables. Also the range of available Earth Observation systems exhibits a significantly changing sensitivity to vegetation properties. For example, multiangular and LIDAR measurements are sensitive to canopy structure, whereas spectral measurements can be specifically related to variations in the foliage biochemistry and species composition of the canopy (Lefsky et al. 2002; Ustin et al. 2004; Widlowski et al. 2004). Spectral information also shows a strong but indirect relation to the canopy structure. Its sensitivity in this context, however, is limited to certain ranges. The LAI retrieval, based on pure spectral remote sensing, is thus only feasible up to a certain level before saturating (Myneni et al. 2002).

The nature of remote sensing data and its intended use as geospatial information supporting decision-making, leads to a twofold challenge within the interpretation of Earth Observation (figure 1). First, remote sensing data contain generally only limited and often indirect information on the vegetation canopy (Baret et al. 2000; Verstraete et al. 1996). A quantitative and comprehensive retrieval of vegetation properties requires thus additional and independent information (Combal et al. 2003; Gemmell et al. 2002). This information can be obtained by complementary Earth Observation sensors or multi-temporal observations delivering independent measurements of the same target. Also ancillary data provided by e.g. meteorological observation systems could be useful. Furthermore, a robust retrieval requires the accurate description of the physical processes involved in the radiative transfer within the canopy (Myneni et al. 1995; Pinty et al. 2004). The second challenge lies in the transformation of the retrieved vegetation properties into information products relevant for the supported decision-making process. Often the interpretation of the retrieved geospatial information on the vegetation makes only sense in a wider biological and ecological context. These requirements lead ultimately to the integration of Earth Observation into canopy functioning or land surface process models (Baret et al. 2000; Running et al. 1999). Finally, in view of the increased use of Earth Observation for surveillance of environmental policies, such as the implementation of the Kyoto protocol, an enhanced interface between scientists and political decision makers is needed to ensure a consistent interpretation of the data (Rosenqvist et al. 2003a; Zimmerer and Bassett 2003).

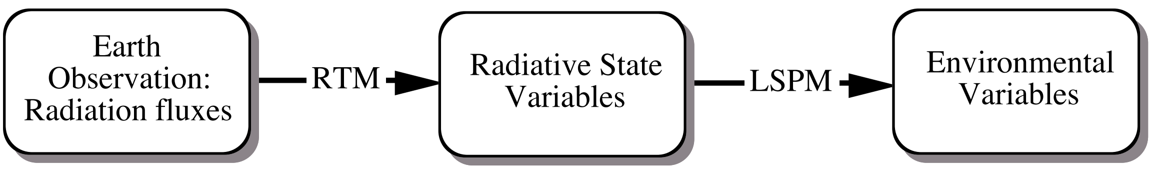


Figure 1. Information flow from Earth Observation to the information products relevant for decision-making using radiative transfer models (RTM) and land surface process models (LSPM) (based on Verstraete et al., 1996).

## Dimensions of Earth Observation for vegetation characterization

Earth Observation obtains data from the vegetated surface in several independent information dimensions - the spatial, spectral, directional and temporal dimension will be here addressed. Due to the complex nature of vegetation canopies, independent observations are necessary for its comprehensive and robust characterization. Earth Observation data over vegetation also exhibit large variability in each of the information dimensions. The variability is caused by a high heterogeneity of canopy structure in the horizontal and vertical space, a variable biochemical composition and a dynamic temporal evolution. The different information dimensions of Earth Observation and their exploitation in respect to the retrieval of vegetation characteristics are discussed in the following separately. To constrain the following discussion, it will be restricted to sensors operating in the optical region (visible to shortwave infrared) of the electromagnetic spectrum. Also the polarimetric information dimension of Earth Observation is not included since atmospherically induced polarization effects disturb top of atmosphere measurements in the visible spectrum (Deschamps et al. 1994).

### Spatial information dimension

Variation of vegetation properties in space can be observed in horizontal as well as in vertical dimension from remote sensing platforms. As a three dimensional and semi-transparent medium, vegetation impacts the radiation fluxes measured by Earth Observation by the distribution of its canopy elements in horizontal as well as vertical dimension. The Earth Observation signal of vegetation thus carries information on the spatial heterogeneity, canopy structure and height.

In the horizontal extension of the spatial dimension Earth Observation for vegetation has been mainly based on measures of the local variability or image texture (Colombo et al. 2003; Curran 2001; Song and Woodcock 2002). The image texture in this context can be described by statistical measures of the spatial variability in neighboring image elements (Wulder 1998). A more comprehensive assessment of the spatial image variation is the variogram, a geostatistical measure (Woodcock et al. 1988). An image variogram can be diagnostic of vegetation features as tree density and size within an observed scene (Atkinson and Lewis 2000). The usefulness of spatial information for the above concepts depends on the spatial resolution of the remote sensing data relative to the objects size of interest. Generally the local variance reaches a maximum at a spatial resolution of 0.75 of the object size dominating the observed scene (Woodcock and Strahler 1987).

The active optical Earth Observation system LIght Detection And Ranging (LIDAR) provides direct measurements on the vertical distribution of canopy elements within a vegetation canopy (Dubayah and Drake 2000; Lefsky et al. 2002; Naesset and Bjerknes 2001). The measurement principle of LIDAR relies on laser pulses propagating vertically through the canopy, while scattering events are recorded as function of time. The remote sensing technique LIDAR is thus particularly suited to derive vegetation properties such as tree elevation, the vertical profile of foliage and terrain height (Harding et al. 2001). The high resolution of small footprint LIDAR even allows for the three dimensional geometric reconstruction of single trees within a forest (Hyyppa et al. 2001; Morsdorf et al. 2004). It has been also shown that multi-angular measurements are sensitive to vertical canopy structure, but with a lower accuracy and resolution than assessable with LIDAR data (Kimes et al. 2006).

### Spectral information dimension

The spectral information contained in Earth Observation data over vegetated surfaces is based mainly on absorption features in the canopy reflectance spectrum related to the biochemistry of the vegetation. Although scattering processes at foliage and canopy level cause alteration of the canopy reflectance in the near infra-red spectral range, most of its spectral variability is induced by absorption due to different biochemical foliage compounds (Curran 1989; Dawson et al. 1999).

Imaging spectroscopy, with its high number of contiguous and narrow spectral bands, is able to capture most absorption features inherent to a vegetation reflectance spectrum (Green et al. 1998; Ustin et al. 2004). A number of different biochemical compounds have thus been proved retrievable from the spectral information dimension of Earth Observation: e.g. foliage chlorophyll content (Daughtry et al. 2000; Jacquemoud et al. 1996; Zarco-Tejada et al. 2004), foliage water content (Ceccato et al. 2002; Danson et al. 1992; Serrano et al. 2000) and dry matter, litter or wood (Asner et al. 2000; Fourty and Baret 1997; Roberts et al. 2003). The enhanced spectral information content of imaging spectrometer data also allows for the mapping of species composition, plant functional types and floristic indicators (Asner and Vitousek 2005; Martin et al. 1998; Schmidtlein 2005; Ustin et al. 2001). More recently also plant stress induced fluorescence has been extracted from narrowband spectral data (Middleton et al. 2005; Perez-Priego et al. 2005; Zarco-Tejada et al. 2000).

The spectral contrast between the red and the near infrared inherent in a vegetation spectrum is the most exploited spectral information content of Earth Observation for vegetation studies (Baret and Guyot 1991; Gamon et al. 1995; Tucker 1979). Most studies are based on vegetation indices related to canopy properties such as LAI, canopy cover, FAPAR and biomass computed from broadband spectral data, although the advantage of hyperspectral data has been also recently shown (Gobron et al. 2000; Lee et al. 2004; Running et al. 1986; Schlerf et al. 2005). Nevertheless, spectral observation alone only relates indirectly to canopy structural properties and may be disturbed by additional factors such as background reflectance and heterogeneity (Asner 1998; Myneni et al. 1995; Verstraete et al. 1996).

### Directional information dimension

Multiangular Earth Observation measurements can characterize the surface reflectance anisotropy, which can be diagnostic for vegetation structure. Further, they are also able to improve the estimation of directionally integrated measures, such as surface albedo and FAPAR (Fraction of Absorbed Photosynthetic Active Radiation) (Diner et al. 2005; Gobron et al. 2002).

The amplitude of the anisotropy pattern is mainly driven by the optical properties of the canopy elements, increased by scattering processes. The shape of the surface anisotropy depends on the canopy structure described by its geometric canopy properties, architecture and heterogeneity (Asner et al. 1998; Gerard and North 1997; Goel 1988; Pinty et al. 2002). The reflectance anisotropy is thus directly related to the surface structure. A number of studies have estimated canopy structure parameters such as LAI, canopy cover and sub-pixel heterogeneity based on multiangular measurements (Chen et al. 2003; Chopping et al. 2003; Widlowski et al. 2004). Specifically, the Minnaert function parameter, as implemented in the RPV model, has been shown to be sensitive to horizontal and vertical canopy heterogeneity under certain illumination condition (Pinty et al. 2002; Widlowski et al. 2001). Furthermore, significant correlation between LIDAR based canopy height measurements and multiangular observations implied a sensitivity of reflectance anisotropy to vertical canopy structure (Kimes et al. 2006).

Multiangular Earth Observation also showed potential to distinguish different land cover and surface types of different structural characteristics (Barnsley et al. 1997; Brown de Colstoun and Walthall 2006; Pinty et al. 2000; Sandmeier and Deering 1999). Finally, the joint use of multiangular and spectral data showed an increased robustness and accuracy of retrieval for LAI and FAPAR relative to single-angle observations (Hu et al. 2003; Myneni et al. 2002; Rast 2004).

**Temporal information dimension**

Earth Observation reveals a high dynamic at several different time scales ranging from diurnal over seasonal to long-term scales. The variability and evolution of the observed canopy reflectance over time is linked to plant physiological processes and changing environmental conditions affecting canopy structure and biochemistry.

At the diurnal time scale, factors such as the illumination conditions and water stress, drive processes like photosynthesis and changes in canopy architecture, which alter the canopy reflectance (Danson and Aldakheel 2000; Drolet et al. 2005; Kimes and Kirchner 1983; Zarco-Tejada et al. 2000). In addition, the effect of changing solar position on canopy reflectance, due to its surface anisotropy, has been shown (Strub et al. 2002).

On a regional to continental scale key phenological variables, such as start, end and length of season, have been retrieved from seasonal Earth Observations mainly based on vegetation indices (Moulin et al. 1997; Schwartz et al. 2002; Zhang et al. 2003). Interannual variation in the length of the phenological cycle as observed by satellites has been shown to carry implications for the productivity of the vegetation. These observations were concordant with changes in the atmospheric $CO_2$ cycle (Myneni et al. 1997; Tucker et al. 2001). In the context of precision farming Earth Observation is able to deliver spatial and temporal intra-field variability of biophysical vegetation properties describing the crop status over the season (Baret et al. 2000; Doraiswamy et al. 2003; Moran et al. 1997). Current research evolves to an integration of multi-temporal remote sensing data into crop growth models, since these models provide a continuous estimate of crop development over time whilst remote sensing assesses the spatial distribution of instantaneous crop conditions at certain phenological stages (Guerif and Duke 2000; Verhoef and Bach 2003a; Weiss et al. 2001). By the use of variables derived from Earth Observation such as LAI, FAPAR or biomass, crop growth models can be recalibrated, updated or even forced (Delecolle et al. 1992; Prevot et al. 2003).

At long term scale, Earth Observation of forest succession and disturbances plays a major role for characterizing the temporal evolution of the vegetation canopy. Forest succession has been linked in numerous studies to forest age classes or different succession stages exploiting the spectral information of remote sensing (Cohen et al. 1995; Fiorella and Ripple 1993; Kimes et al. 1999). Furthermore, estimates of canopy structure based on Earth Observation have been shown to be indicative to successional stages of forest stands (Danson and Curran 1993; Roberts et al. 2004). However, the relationship between the spectral signature and the forest succession is highly nonlinear over time, due to changing impact of factors such as background and shadow effects with increasing canopy cover (Nilson and Peterson 1994; Song et al. 2002). Finally, the frequency and spatial extent of human or natural disturbances are important for the understanding and long term monitoring of the forest ecosystem (Schimel et al. 1997). Earth Observation methods have been thus developed to detect patterns in time and space of disturbances such as fire, logging or insect damage (Li et al. 1997; Potter et al. 2003; Ranson et al. 2003).

## Radiative Transfer within a vegetation canopy

The Earth Observation signal of a vegetation canopy is known to be primarily a function of the foliage optical properties, canopy structure and architecture, background reflectance of understory and soil, illumination conditions and viewing geometry (Chen et al. 2000; Goel 1988; Ross 1981). Earth Observation, acquired from air- or spaceborne systems, can be thus considered as a signature of the complex absorption and scattering processes within the vegetation canopy (Asner 1998; Dawson et al. 1999). It has been shown that the radiative transfer determining the canopy reflectance is influenced basically at the leaf and the canopy level (Baret et al. 1994; Panferov et al. 2001). These two levels of radiative interactions will be discussed in the following separately.

### Leaf level

The understanding of the radiative transfer at the leaf level requires a profound knowledge of the molecular based absorption characteristics of the foliar chemical components, such as electronic transitions in the chlorophyll pigments or the bending and stretching vibrations of the biochemical bonds (Curran 1989; Lichtenthaler 1987). In the optical region of the electromagnetic spectrum the foliage affects radiation within the canopy by its reflectance and transmittance characteristics. These foliage optical properties are primarily a function of internal leaf structure, leaf surface roughness, water content and the foliar chemical components (Bousquet et al. 2005; Fourty et al. 1996; Middleton et al. 1997; Ross 1981). Consequently, a full understanding of the relationship between the processes governing the foliage optical properties, such as light absorption and scattering, and the leaf biochemical concentrations is critical (Jacquemoud et al. 1996). A number of experiments have shown significant correlation between the leaf biochemical composition and the corresponding leaf optical properties by either empirical or analytical means (Curran et al. 2001; Daughtry et al. 2000; Fourty et al. 1996; Jacquemoud et al. 1996; Peterson et al. 1988). In general, measurements were conducted with the combined use of a high-resolution spectrometer and an integrating sphere to describe the hemispherical leaf reflectance and transmittance, along with standard wet-laboratory procedures to determine the biochemistry (Curran 1989; Daughtry et al. 1989).
Physically based models describing the radiative transfer within the leaf are required to investigate the causal relationships between foliage optical properties and the foliage biochemistry in detail (Dawson et al. 1998; Ganapol et al. 1998; Jacquemoud and Baret 1990). The inversion of a leaf radiative transfer model allows a highly accurate retrieval of the respective single biochemical leaf constituent as proven by Jacquemoud et al., 1996 in the LOPEX experiment.

### Canopy level

Estimates of vegetation properties based on Earth Observation from air- or spaceborne platforms have to be ultimately assessed on the canopy level. Numerous studies investigated the effects on leaf optical properties during the transition from the leaf level to the canopy scale (Asner and Wessman 1997; Baret et al. 1994; Dawson et al. 1999; Kupiec and Curran 1995; Zarco-Tejada et al. 2001). Asner, 1998 identified the canopy structure, specifically the LAI, Leaf Angle Distribution (LAD) and fractional cover (fcover) as well as the leaf optical properties, the nonphotosynthetic canopy elements and the understory as the main factors driving the canopy reflectance signal. Several authors pointed out the important influence of the understory and background reflectance on the canopy level, especially for canopies with low vegetation cover (Huemmrich and Goward 1997; Spanner et al. 1990).

For heterogeneous canopies such as boreal forests canopy architecture and geometry have to be considered on needle, shoot and on the crown level as well as the distribution of trees within the forest stands (Chen and Leblanc 1997; Chen et al. 1997; Rautainen et al. 2004; Stenberg 1998; Williams 1991). In spite of the numerous influencing factors, the foliage biochemistry is retrievable from canopy reflectance. The dominating multiple scattering process in the near infrared, induced by the canopy structure, is in fact enhancing the leaf optical properties features increasing the potential of biochemistry retrieval (Baret et al. 1994).

### Radiative transfer modeling

Radiative transfer models (RTM) are quantitative tools for linking measurements of radiation fluxes to the parameters and physical processes that control these observations. RTM thus relate the Earth Observation signal of a vegetation canopy to the canopy characteristics considering the incident radiation and the physical processes that govern the radiative transfer within the canopy (Goel and Thompson 2000; Kimes and Kirchner 1982; Ross 1981).

The simulation of the Earth Observation signal for specific canopy representations by an RTM in its direct or forward mode (figure 2) is essential for the validation and intercomparison of the different RTM implementations (Jacquemoud et al. 2000; Myneni et al. 1995; Pinty et al. 2001). Forward RTM simulation also allow for sensitivity studies of canopy parameters relative to diverse observation specifications. This can lead to an improved understanding of the remote sensing signal as well as to an optimized instrument design of future Earth Observation systems (Bacour et al. 2002; Gobron et al. 1997; Verhoef and Bach 2003b; Weiss et al. 2000).

For the retrieval of vegetation properties an RTM has to be inverted against Earth Observation data (figure 2). A prerequisite of a successful inversion is the choice of a validated and appropriate RTM, which correctly represents the radiative transfer within the observed target (Pinty and Verstraete 1992). The unique and explicit solution for a RTM inversion depends on the number of free model parameters relative to the number of available independent observations. The inversion of a RTM is generally undetermined and hence represents a ill-posed problem, due to the number of parameters necessary to describe the complex system of a vegetation canopy and uncertainties related to the RTM and measurements (Combal et al. 2003; Verstraete et al. 1996). Different numerical approaches with changing advantages have been applied to solve the generally underdetermined problem of a canopy RTM inversion (Kimes et al. 2000; Tarantola 2005). The inversion of a canopy RTM offers a quantitative retrieval of vegetation properties. Given their physically based nature, RTM show an increased robustness and accuracy over time and space compared to empirical approaches (Kimes et al. 2000; Verstraete et al. 1996).

Radiative transfer modeling in canopies with a high heterogeneity in the horizontal and as well in the vertical dimension require 3-D radiative transfer models since the interaction of incident radiation is dominated by the complex canopy structure (Dawson et al. 1999; Gastellu-Etchegorry and Bruniquel-Pinel 2001). Several canopy RTM are available parameterizing the canopy and consequently the radiative transfer in different complexities (e.g. (Chen and Leblanc 1997; Disney et al. 2000; Govaerts and Verstraete 1998; Huemmrich 2001; Ni et al. 1999; North 1996)). Unfortunately, with increasing complexity of the model the retrieval of canopy parameters is limited due to the generally ill-posed nature of the RTM inversion (Combal et al., 2003). Nevertheless, the inversion of rather simple geometric-optical models and even of sophisticated hybrid models showed promising results in retrieving biophysical and biochemical parameters of heterogeneous canopies (Kuusk, 1998; Demarez & Gastellu-Etchegorry, 2000; Hu et al., 2000; Gemmell et al., 2002). Although RTM have been mostly applied for the exploitation of optical Earth Observation, RTM have been also developed and applied for other remote sensing systems, including LIDAR and RADAR sensors (Disney et al. 2006; Kimes et al. 1997; McDonald and Ulaby 1993; Ni-Meister et al. 2001; Ranson et al. 1997; Sun and Ranson 2000).

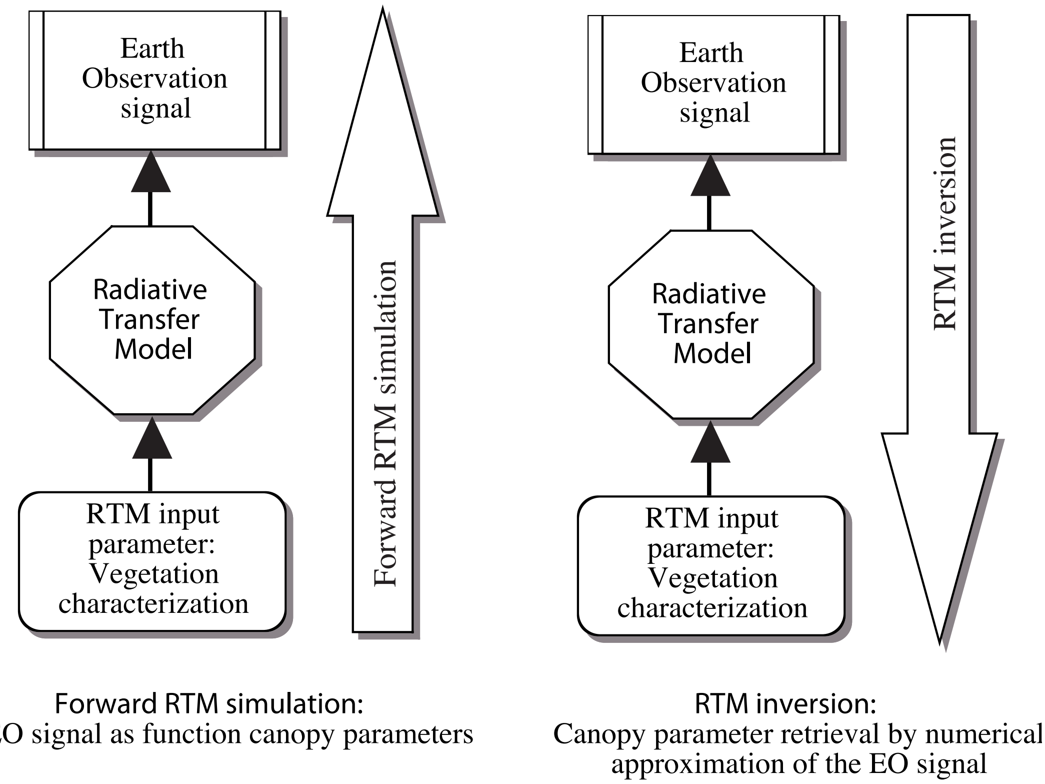


Figure 2. Conceptual scheme of radiative transfer modeling in its forward and inverse mode.

## Rationale of Dissertation

### Motivation

Multispectral and multiangular data provided by imaging spectrometers, return signals from both large- and small-footprint LIDAR as well as backscattering coefficient data from imaging radar are now available for Earth Observation of the vegetated land surface. The MODIS and MISR sensors on the NASA Terra/Aqua platforms, the ESA mission CHRIS on Proba, PALSAR on ALOS operated by JAXA, GLAS on board of IceSAT or the airborne system LVIS are selected examples of recent Earth Observation systems. Data from these sensors contain independent information relevant to different aspects of the biochemical and biophysical properties of the vegetation canopy. Consequently the combined exploitation of these remote sensing capabilities will significantly improve the potential and accuracy of extracting vegetation properties using Earth Observation methodology.

A number of studies have already pointed out the potential of the combined use of different Earth Observation dimensions and wavelength domains. The combination of imaging spectroscopy and synthetic aperture RADAR has significantly enhanced the estimation of leaf area density and biomass compared to their individual estimates based on the respective sensor system (Treuhaft et al. 2002; Treuhaft et al. 2004). Similarly the synergy of spectral and directional Earth Observation has been shown efficient for an improved estimation of vegetation properties (Knyazikhin et al. 1998; Widlowski et al. 2004). Furthermore, spectral measurements complemented by LIDAR data achieved increased accuracy in mapping species composition and vegetation structure for ecological applications and forestry inventories (Blackburn 2002; Gillespie et al. 2004; Hill and Thomson 2005; Leckie et al. 2003; Popescu et al. 2004). Finally, complementing and initial research, conducted during but not directly included in the presented dissertation, showed the use of combining spectral Earth Observation dimension with additional information derived from the spatial (Koetz et al. 2003; Kötz et al. 2003), the temporal (Koetz et al. 2005a) and the directional dimension (Koetz et al. 2005b).

The robust and operational estimation of vegetation properties based on Earth Observation that span the entire range of realistic vegetation conditions require the use of physically based radiative transfer modeling (Myneni et al. 2002; Verstraete et al. 1996). Radiative Transfer Models (RTM) initially developed for homogenous vegetation canopies have been extended over the years to the full 3-D characterization of the radiative transfer within heterogeneous canopies. Furthermore, models are now able to describe the radiative transfer in canopies at different wavelength domains from the optical to microwave range as well as to implement passive and active sensor specifications. Incorporating the present knowledge of physical processes involved in the radiative transfer, the RTM inversion is a promising methodology to derive a robust and comprehensive characterization of the complex and dynamic nature of vegetation canopies. RTM inverted against the full capability of Earth Observation potentially provide quantitative and continuous estimates of canopy parameters ranging from leaf area index (LAI), fractional cover, tree height to foliage chlorophyll and water content.

Recent developments in radiative transfer modeling and the availability of independent information dimensions provided by current and future Earth Observation platforms enable to describe and thus solve the radiative transfer equation with increased accuracy and stability. This approach potentially leads to improved global, comprehensive and quantitative vegetation characterizations that fulfill the requirements of ecological and political driven services.

**Objectives**

The presented dissertation addresses open questions related to the retrieval of biophysical and biochemical properties of heterogeneous canopies by remote sensing methods. The approach taken focuses on modeling the radiative transfer within the heterogeneous canopy of coniferous forests to derive quantitative information on the canopy structure and on foliar biochemistry. The approach of radiative transfer modeling has been chosen due to its explicit description of the relationship between the canopy properties, the observation and illumination conditions and the resulting Earth Observation signal. The thesis will concentrate on the combined exploitation of the independent information dimensions provided by the two Earth Observation systems imaging spectrometry and LIDAR for the characterization of heterogeneous canopies.

Imaging spectrometry and LIDAR provide independent information of contrasting but complementary content. The information dimension observed by LIDAR contains direct measurements of the canopy structure describing the canopy height and the vertical distribution of canopy elements. On the other hand, the spectral information dimension obtained by imaging spectrometers contains information about the biochemical composition of the canopy foliage and only an indirect link to the canopy structure. However, the leaf optical properties, which are directly related to the foliage biochemistry, scale to the canopy as a function of canopy structure and spatial arrangement of canopy elements. Furthermore, the geometric primitives of the canopy structure, such as crown size and spatial tree arrangement, dominate the radiative transfer within a heterogeneous canopy. Consequently the LIDAR signal, e.g. recorded as full waveform, can improve the accuracy and robustness of canopy parameter retrieval by reducing uncertainties related to the canopy structure. On the other hand, the accurate interpretation of the LIDAR signal depends on the spectral properties of canopy elements as well as the background. The two sensors and their different information dimension are thus mutually dependant and can complement each other. A combined exploitation of the information dimensions observed by imaging spectrometry and LIDAR based on radiative transfer modeling will therefore provide a novel and unique approach to optimize the retrieval of forest foliage biochemical composition and canopy structure.

Based on the scientific motivation and objectives from above the following research questions have been developed and will be investigated in this dissertation:

- Is a model capable of representing the radiative transfer within a heterogeneous canopy, such as a coniferous forest? (investigated in publication 1 and 2)
- Can an RTM, appropriately describing the radiative transfer relevant for imaging spectroscopy, be inverted over a heterogeneous canopy? (investigated in publication 1)
- Can an RTM, appropriately describing the radiative transfer relevant for LIDAR, be inverted over a heterogeneous canopy? (investigated in publication 2)
- What model assumptions and parameterizations have to be made for a successful inversion of the respective RTM? (investigated in publication 1-3)
- How can the specific information content of the two Earth Observation systems imaging spectrometry and LIDAR be integrated into a combined retrieval algorithm? (investigated in publication 3)
- Can the developed methodology be generalized for the requirements of future multiple-sensor Earth Observation missions? (investigated in publication 3)

## Structure

### *Part A: Scientific Setting*

A general background, introduction and problem description are given in the scientific setting of the dissertation. The requirements and available information dimensions of Earth Observation for vegetated land surface applications are presented. Further, the general challenges and underlying processes relevant for remote sensing of vegetation canopies are discussed. Finally, the motivation and objectives of the presented thesis are detailed.

### *Part B: Publications*

The scientific objectives of the dissertation have been addressed and the yielding results presented in three subsequent journal publications. The first two publications separately discuss the interpretation of the Earth Observation signal of imaging spectrometry and LIDAR based on the inversion of respective RTM. The contribution published in the special issue Forest Fire Prevention and Assessment of the Journal of Remote Sensing of Environment (Kötz et al. 2004) *Radiative transfer modeling within a heterogeneous canopy for estimation of forest fire fuel properties* demonstrated the feasibility of retrieving structure and foliage water content of a coniferous canopy from imaging spectrometry based on radiative transfer modeling. The second publication presented in the IEEE Geoscience and Remote Sensing Letters (Koetz et al. 2006) *Inversion of a LIDAR Waveform Model for Forest biophysical Parameter Estimation* verified the invertibility of a LIDAR waveform RTM and its potential to retrieve horizontal and vertical forest structure from large-footprint LIDAR data. The final contribution describing the synergistic exploitation of imaging spectrometer and LIDAR data for a comprehensive and improved canopy characterization based on the two linked RTM addressed in the two previous publications is forthcoming in the Journal of Remote Sensing of Environment under the title *Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization* (Koetz et al. 2006 (submitted)).

### *Part C: Synopsis*

The progress and major findings of the single publications are summarized and discussed in the context of the dissertation research questions. Furthermore, the perspective and future challenges in the research field of the presented thesis are addressed and final conclusions are drawn.

## Practical context

The dissertation has been initiated and partly conducted within the framework and context of the European Community project ‘Forest Fire Spread and Mitigation’ (SPREAD). The objective of SPREAD was the understanding and assessment of main factors involved in the managing of forest fires as a natural hazard. The project focused on the different aspects related to prevention, behavior and effects of forest fires as well as how these could be integrated into a decision support system for fire management. The work of the dissertation contributed to the objectives of SPREAD by developing an innovative methodology for forest fire fuel description based on Earth Observation. Forest fire risk and behavior depend heavily on fuel properties such as the quantity of biomass, partitioning of living and dead biomass, moisture content and the vertical and horizontal canopy structure (Chuvieco et al. 2002; Lynham et al. 2002). The observations of imaging spectrometry and LIDAR have been identified as an innovative tool for the mapping of such fuel properties. The research conducted within this dissertation provided a methodology to derive a comprehensive

canopy characterization relevant for the spatial description of fuel properties. Accurate spatial information on forest fuel properties is vital for the understanding of processes involved in initiation and propagation of forest fires (Chuvieco 2003; Keane et al. 2001).
The developed methodology has been validated on field data acquired in the Eastern Ofenpass valley, which is part of the Swiss National Park (SNP). The Ofenpass represents an inner-alpine valley at an average altitude of about 1900 m a.s.l., with an annual precipitation of 900-1100 mm. The forest stands within the study area can be classified as woodland associations of *Erico-Pinetum mugo* (Zoller 1995). The understory is characterized by low and dense vegetation composed mainly of *Ericaceae* and *Sesleria* species. The test site has been selected due to its boreal type forests, which allow to draw conclusions relevant for the large biome of boreal forests. Furthermore, the observed forest has been affected by few but intense (stand-replacing) fires.

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# PART B: PUBLICATIONS OF THE DISSERTATION

# First Publication

## Radiative transfer modeling within a heterogeneous canopy for estimation of forest fire fuel properties

Kötz, B., Schaepman, M., Morsdorf, F., Bowyer, P., Itten, K., & Allgöwer, B. (2004). Radiative transfer modeling within a heterogeneous canopy for estimation of forest fire fuel properties. *Remote Sensing of Environment*, 92, 332-344

Available online at www.sciencedirect.com

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Remote Sensing of Environment 92 (2004) 332–344

Remote Sensing of Environment

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# Radiative transfer modeling within a heterogeneous canopy for estimation of forest fire fuel properties

Benjamin Kötz[a,*], Michael Schaepman[b], Felix Morsdorf[a], Paul Bowyer[c], Klaus Itten[a], Britta Allgöwer[d]

[a] Department of Geography, Remote Sensing Laboratories, University of Zurich, Winterthurerstrasse 190, Zurich CH-8057, Switzerland
[b] Centre for Geo-Information, Wageningen University and Research Centre, Droevendaalsesteeg 3 NL-6708 PB Wageningen, The Netherlands
[c] Telford Institute of Environmental Systems, School of Environment and Life Science, University of Salford, Manchester, United Kingdom
[d] Geographic Information Systems, Dept. of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

Received 19 July 2003; received in revised form 21 May 2004; accepted 24 May 2004

## Abstract

Imaging spectrometer data were acquired over conifer stands to retrieve spatially distributed information on canopy structure and foliage water content, which may be used to assess fire risk and to manage the impact of forest fires. The study relied on a comprehensive field campaign using stratified systematic unaligned sampling ranging from full spectroradiometric characterization of the canopy to conventional measurements of biochemical and biophysical variables. Airborne imaging spectrometer data (DAIS7915 and ROSIS) were acquired parallel to the ground measurements, describing the canopy reflectance of the observed forest. Coniferous canopies are highly heterogeneous and thus the transfer of incident radiation within the canopy is dominated by its structure. We demonstrated the viability of radiative transfer representation and compared the performance of two hybrid canopy reflectance models, GeoSAIL and FLIGHT, within this heterogeneous medium. Despite the different nature and canopy representation of these models, they yielded similar results. Subsequently, the inversion of a hyperspectral GeoSAIL version demonstrated the feasibility of estimating structure and foliage water content of a coniferous canopy based on radiative transfer modeling. Estimates of the canopy variables showed reasonably accurate results and were validated through ground measurements.


*Keywords:* Imaging spectroscopy; radiative transfer; coniferous canopy; canopy structure; foliage water content; forest fire

## 1. Introduction

Three major forces are essential for understanding forest fire risk and specifically fire behavior—weather, fuel and topography—as illustrated by the *fire environment triangle* (Countryman, 1972; Pyne et al., 1996). Within this concept, the fire fuel component introduces high uncertainty to the prediction of fire hazard due to its high spatial and temporal variability.

Fire risk and behavior depend heavily on the fuel properties such as the quantity of biomass, partitioning of living and dead biomass, moisture content, and the vertical and horizontal structure of the canopy (Chuvieco et al., 2002; Lynham et al., 2002). Accurate information on forest fuel properties at high spatial and temporal resolutions is vital for understanding the processes involved in initiation and propagation of forest fires (Chuvieco, 2003; Keane et al., 2001). Remote sensing offers the potential to provide spatially distributed information on biomass, canopy structure, and fuel moisture to assess fire risk and to mitigate the impact of forest fires (Chuvieco & Congalton, 1989; Dennison et al., 2003; Fraser & Li, 2002; Leblon, 2000; Roberts et al., 2003).

The spectral reflectance of a plant canopy is known to be primarily a function of the foliage optical properties, the canopy structure, the understory and soil background reflectance, the illumination conditions, and finally, the viewing geometry (Chen et al., 2000; Goel, 1988). Radiative transfer modeling takes into account physical processes describing the interaction of radiation with the diverse canopy components at foliage and canopy levels. Consequently, a physically based approach of coupled leaf and canopy radiative transfer models (RTMs) provides an adequate way to assess canopy variables, such as vegetation water content and leaf area index (LAI). Radiative transfer models have already been

* Corresponding author. Tel.: +41-1-635-5251; fax: +41-1-635-6846.
*E-mail address:* bkoetz@geo.unizh.ch (B. Kötz).

0034-4257/$ - see front matter 
doi:10.1016/j.rse.2004.05.015

successfully employed with homogeneous canopies to derive quantitative information on canopy structure and foliage biochemistry (Fourty & Baret, 1997; Jacquemoud et al., 2000; Weiss et al., 1999). Over the past few years, research in this area has been extended to the full characterization of the radiative transfer within heterogeneous canopies such as deciduous and coniferous forests (Dawson et al., 1999; Gastellu-Etchegorry & Bruniquel-Pinel, 2001). Forest canopies are characterized by high horizontal and vertical heterogeneity. Coniferous forests, in particular, exhibit a complex canopy structure which has to be considered at the needle and shoot levels, assessing the well-known clumping effect of needles, at the crown level, and at the forest stand level (Cescatti, 1998; Chen et al., 1997a; Chen & Leblanc, 1997; Williams, 1991). Consequently, the radiative transfer within a forest canopy depends on the spatial distribution of the canopy elements relative to each other and on the subsequent complex radiative processes such as multiple scattering, mutual shading of the crowns, and shading of the background. In this case, three-dimensional canopy radiative transfer models are required to parameterize the heterogeneous canopy structure appropriately (e.g. Chen & Leblanc, 1997; Govaerts & Verstraete, 1998; Huemmrich, 2001; North, 1996). Unfortunately, the inverse solution of a RTM is not necessarily unique, limiting the estimation of canopy variables. The ill-posed nature of the RTM inversion increases with the complexity of the observed medium and the employed model (Combal et al., 2003). However, various physically based canopy reflectance models have been used to estimate biophysical and biochemical variables of heterogeneous canopies with promising results (Demarez & Gastellu-Etchegorry, 2000; Gemmell et al., 2002; Hu et al., 2000; Kimes et al., 2002; Kuusk, 1998; Zarco-Tejada et al., 2001).

Imaging spectrometry from air- or spaceborne platforms gives access to the spectral features of canopy reflectance caused by the complex absorption and scattering processes within the canopy (Asner et al., 2000; Rast, 2001; Schaepman et al., in press). In this study, we utilized two hybrid radiative transfer models applied to imaging spectrometer data acquired over a coniferous forest to estimate canopy variables relevant for the description of forest fuel properties. The specific objective of this study is to evaluate the ability of the two selected radiative transfer models, FLIGHT (North, 1996) and GeoSAIL (Huemmrich, 2001), to represent the complex nature, and consequently, the reflectance of a heterogeneous canopy. We compare the two radiative transfer models and assessed the influence of the different complex canopy representations—inherent to the selected models—on the characterization of the canopy reflectance. The inversion of GeoSAIL assesses subsequently the feasibility of canopy variable estimation by radiative transfer modeling and imaging spectroscopy over a heterogeneous canopy. The final validation involves a comprehensive canopy characterization based on ground measurements along with a quality assessment of the imaging spectrometer data (Kötz et al., 2003). This enabled a full validation of the proposed methodology including the definition of the relevant uncertainties of all contributing error sources based on ground measurements, the image data, and the model inversion.

### *1.1. Background: fuel properties and remote sensing*

Imaging spectroscopy can provide a number of canopy properties relevant for forest fire issues such as green vegetation water content (Ceccato et al., 2001; Gao & Goetz, 1995; Penuelas et al., 1997; Serrano et al., 2000; Ustin et al., 1998) or biomass loads (De Jong et al., 2003; Roberts et al., 2003). However, canopy parameters assessed by remote sensing are not necessarily directly compatible with the requirements of the fire research and management community. In the forest fire literature, vegetation water content is traditionally expressed as fuel moisture content (FMC), defined as the percentage of water weight over sample dry weight (Chuvieco et al., 2002). Whereas in remote sensing, water content in vegetation is characterized by the equivalent water thickness (EWT: water content per leaf area; Danson et al., 1992; Tucker, 1980) because this variable is directly related to the leaf optical properties (Ceccato et al., 2001, 2002b). However, EWT derived from remote sensing is easily converted into FMC values by introducing information on the specific leaf weight (Chuvieco et al., 2003a). Another important fuel property is the biomass present in the canopy, commonly expressed as fuel loading, which is usually taken into account within the respective fuel model (Pyne et al., 1996). Remote sensing observations are best related to canopy biomass by the green leaf area relative to ground surface, the LAI. Foliage biomass can be directly computed from LAI using the specific leaf weight (Keane et al., 2001; Scott & Reinhardt, 2001).

The proposed approach of this study provided all canopy characteristics—EWT, LAI, and leaf dry matter—necessary to describe two important fuel properties, live fuel moisture, and green fuel loading of conifer tree crowns with remote sensing data. Moreover, estimates of the canopy cover can complement the information on the presence of canopy fuels and help to calculate variation of dead fuel moisture (Chuvieco et al., 2003b; Finney, 1998). A direct measure of the live fuel moisture and biomass, as presented here, can be a valuable input for fire behavior modeling. Both live fuel moisture and biomass ideally represent the high temporal and spatial variability of fuels due to numerous influencing environmental factors. Spatial information on live fuel properties is especially critical to fire propagation and could therefore improve predictions of fire behavior models significantly (Carlson & Burgan, 2003; Finney, 1998; Sero-Guillaume & Margerit, 2002).

## 2. Study site and data description

The study area for the acquisition of the field data is located in the Eastern Ofenpass valley which is part of the

Swiss National Park (SNP). The Ofenpass represents an inner-alpine valley at an average altitude of about 1900 m a.s.l, with an annual precipitation of 900–1100 mm. Embedded in this environment are boreal type forests where few, but very impacting (stand-replacing) fires, were observed. The ecology, and in particular, the natural fire regime of these stands are subject to ongoing long-term fire history and disturbance studies in the same area (Allgöwer et al., 2003).

The south-facing Ofenpass forests, the location of the field measurement, are largely dominated by mountain pine (*Pinus montana* ssp. *arborea*) and some stone pine *(Pinus cembra* L.), a second tree specie that is of interest for natural succession (Lauber & Wagner, 1996; Zoller, 1992, 1995). These forest stands can be classified as woodland associations of *Erico–Pinetum mugo* (Zoller, 1995). The understory is characterized by low and dense vegetation composed mainly of various Ericaceae and *Sesleria* species. The study area has been also subject to previous fuel modeling studies where three main fuel models could be identified through extensive field studies (Allgöwer et al., 1998). Therein, model A 'mixed conifers' equals the association *Rhodendro ferruginei–Laricetum*, Model B 'mountain pine' the *Erico–Pinetum mugo*, and model C 'dwarfed mountain pine' the *Erico–Pinetum mugo prostratae*. In the present study, the field measurement were taken within forest stands corresponding to the model B because this is the dominant fuel type of the area.

### 2.1. Sampling scheme

Four core test sites (labeled LWF1, LWF2, STA1, and STA2) and several additional distributed point samples described the canopy and the spectral characteristics of the study area. The core test sites were selected following a stratified sampling scheme to cover different canopy densities within a stand of *P. montana* ssp. *arborea* (Fig. 1). They were set up accordingly to the elementary sampling units of the VALERI scheme (Baret, 2004). Each site was defined by nine sampling points, evenly spaced in a grid spacing of 10 m, covering a square area of 20 × 20 m. The coordinates of the sampling points were georeferenced by nondifferential GPS receivers. Measurements of the biophysical and biochemical variables describing the canopy were performed at all sampling points between the 7th and the 15th of August 2002. Mean values of the core test sites are presented in Table 1.

### 2.2. Canopy structure

Canopy structure was described using two different methods, well known in the literature and adapted to heterogeneous canopies (Chen et al., 1997b; Smolander & Stenberg, 1996). Measurements were carried out using two canopy analyzer LAI2000 (LICOR, 1992) and hemispherical photographs to provide canopy structure variables (EYE-CAN, 2003), separately for the crown and understory layer.

The LAI2000 was used to estimate two canopy variables the effective leaf area index (LAI) and the gap fraction. The LAI2000 provided an effective plant area index representing green foliage and woody area rather than just the green leaf area per unit ground surface area. The clumping effects at the shoot and crown level, typical for coniferous foliage, were corrected following an approach proposed by Chen et al. (1997b). Values for the clumping index of mature *Pinus banksiana* canopies, a tree specie similar to the investigated species, were applied (Chen et al., 1997b). The uncertainties associated with the LAI and the gap fraction provided by the LAI2000 were assessed based on the standard deviation of five reference measurements taken at each measurement point. Observed LAI values ranged between 1.78 and 3.99, whereas the measurement uncertainties amounted to 22%.

Hemispherical photographs taken parallel with the LAI2000 measurements allowed the separation of the canopy into its constituent foliage and wood fractions, i.e., needles, trunk and branches (Jonckheere et al., in press; Weiss et al., in press). The algorithm used relied on a supervised neural network training to classify the photograph into its image elements (EYE-CAN, 2003). Subsequently, the classification technique allowed woody parts and green foliage, and their respective gap fractions, to be distinguished based on their respective colors.

Forest stand measurements of the Long-term Forest Ecosystem Research program of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) were used to describe the basic geometric primitives of the canopy (Fig. 1). Stem density, tree height and crown radius were measured within this program over an area of 2 ha comprising a number of 2456 trees (Table 1). Additionally, the height of the crown base was visually estimated during the field campaign of this study.

### 2.3. Biochemistry of the canopy

Standard wet-laboratory procedures were used for determination of foliage water, chlorophyll content, and dry matter. The samples were collected from the upper part of the tree crowns, each consisting of one branch carrying newly developed and old needles. Due to the temporal variability of the biochemical parameters, the samples were collected on the same day as the overflight, placed in iced, air sealed containers and analyzed in the laboratory during the following 2 days.

The difference between fresh and dry weight allowed for the calculation of water content expressed either as relative value per unit mass [fuel moisture content (FMC) percentage (%)] or per unit leaf area as equivalent water thickness (EWT; g/cm$^2$ or cm). The concentration of photosynthetic pigments (chlorophyll a and b) within the foliage was determined by a CADAS 100 spectrophotometer using the

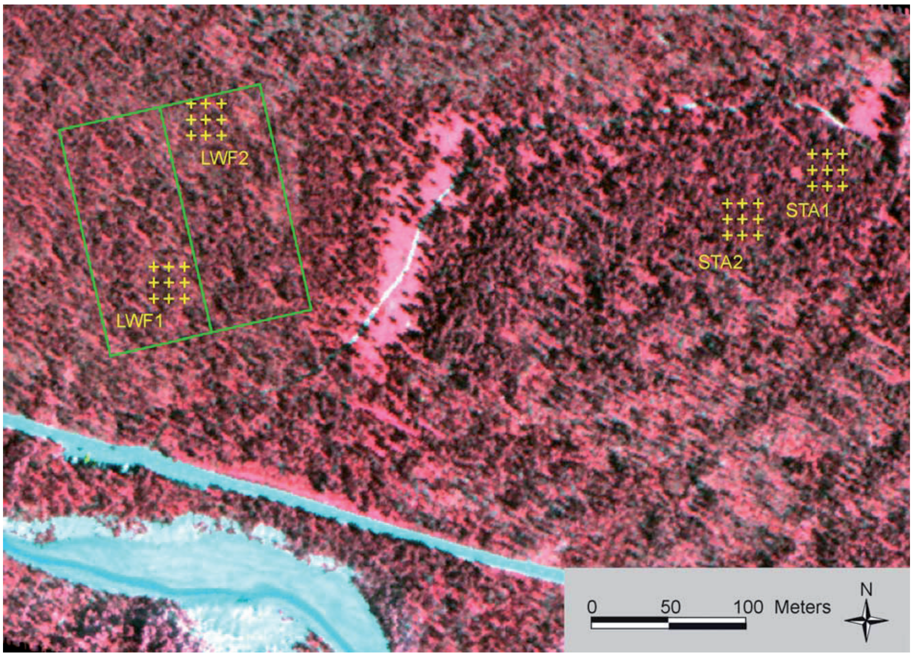


Fig. 1. Airborne imaging spectrometer data over the four core test sites (yellow crosses indicate the sampling points). The image composite represents geocoded and atmospherically corrected data of the spectrometer ROSIS in spatial resolution of 1 m resolving the heterogeneity of the observed forest. The long-term Forest Ecosystem Research site of WSL where forest stand characteristics are acquired is indicated by the rectangle.

Table 1
Field observations of canopy variables including relative measurement errors relevant for the canopy parameterization of the RTMs PROSPECT, GeoSAIL and FLIGHT

| | Unit | LWF1 | LWF2 | STA1 | STA2 |
|---|---|---|---|---|---|
| *Foliage parameters (PROSPECT)* | | | | | |
| Water content | g/cm$^2$ | 0.047 (7.5%) | 0.045 (7.5%) | 0.049 (7.5%) | 0.042 (7.5%) |
| Dry matter | g/cm$^2$ | 0.038 (7.5%) | 0.036 (7.5%) | 0.038 (7.5%) | 0.035 (7.5%) |
| Fuel moisture content[a] | % | 123.7 | 125.0 | 128.9 | 120.0 |
| Chlorophyll content | μg/cm$^2$ | 61.8 (1.54%) | 75.1 (1.54%) | 59.0 (1.54%) | 62.8 (1.54%) |
| Mesophyll structure | unitless | 3.78 (22%) | | | |
| *Canopy structure (overstory)* | | | | | |
| LAI | unitless | 2.18 (13%) | 1.78 (22%) | 3.89 (19%) | 3.99 (17%) |
| Fractional cover | % | 0.55 (13%) | 0.46 (22%) | 0.77 (19%) | 0.79 (17%) |
| Wood fraction | % | 0.3 | 0.3 | 0.3 | 0.4 |
| Crown shape | | Cone | | | |
| Tree distribution | | Poisson distribution | | | |
| *FLIGHT* | | | | | |
| Tree height | m | 11.93 ± 2.9 | | | |
| Crown radius | m | 1.765 | | | |
| Crown base | m | 7 | | | |
| Trunk diameter | m | 0.179 (at ground) | | | |
| Leaf angle distribution | | Spherical | | | |
| *GeoSAIL* | | | | | |
| Crown height width ratio | unitless | 2.83 | | | |
| Hotspot | unitless | 0.1 | | | |
| Leaf angle distribution | | Average leaf angle: 58.43° (foliage) and 30° (woody parts) | | | |

The spectral properties of the woody parts and understory were characterized by spectroradiometric field measurements (Fig. 2).
[a] Calculated after (Chuvieco et al., 2003a,b).

equations of Lichtenthaler (1987). The pigment concentrations were converted to [μg/cm$^2$] by relating the concentration to the leaf area of the sample.

The observed biochemical concentrations showed only a low variability (Table 1) which could be explained by the relative constant environmental measurement conditions. Uncertainties of the estimates of the foliage biochemistry were derived from the accuracy specifications of the respectively involved instruments and reference readings of the measurements.

## 2.4. Spectral properties of canopy components

The spectral properties of several canopy components, including the reflectance of the understory, woody parts, and the foliage, were measured in the field with the ASD field spectroradiometer (Analytical Spectral Devices, 1997). Field spectra were collected during the overflight in nadir measurement configuration, 1.5 m above the ground and within 2 h of solar noon under clear sky conditions. All spectra were converted to absolute reflectance by reference measurements over a Spectralon panel with known spectral properties. The spectral characteristics of branches and bark of trunks were assessed from several selected samples. For the understory, reflectance transects consisting of 10 to 40 spectroradiometric measurements were acquired at each test site (Fig. 2). Measurements of the understory reflectance were affected by shadowing of the crowns. Consequently, spectra lower than one standard deviation relative to the average of the transect were discarded, regarding them as reflectance of shadows.

The acquisition of the reflectance of coniferous foliage involved an ASD field spectroradiometer coupled with an integrating sphere LICOR1800 (LI-COR, 1983) and a custom-made light source for improved illumination. The gap fraction of samples not covering the instrument port was assessed with a high-resolution digital camera and subsequent image analysis. The gap effects on the reflectance measurements were corrected by taking proportionally into account the spectral properties of the background following the approach of Daughtry et al. (1989).

## 2.5. Imaging spectrometer data

The imaging spectrometer data were acquired on the 14th of August parallel to the ground measurements and simultaneously with the DAIS7915 (Chang et al., 1993) and ROSIS sensors (Doerffer et al., 1989). The local illumination and observation conditions were summarized by a solar zenith angle of 45.3°, a solar azimuth angle of 122.9°, and the flight heading of 293°. This study concentrated on the data recorded by the DAIS7915 imaging spectrometer Kennedy scanner which covered a spectral range from the visible to the thermal infrared (VIS/NIR, 0.5–1.1 μm; SWIR1, 1.6–1.8 μm; SWIR2, 2–2.5 μm; MIR, 3–5 μm; TIR, 8.7–13 μm) with 79 bands. The airborne campaign was organized to cover the Ofenpass valley, providing imaging spectrometer data in a spatial resolution of 5 m. The flight line was oriented close to the principal plane of

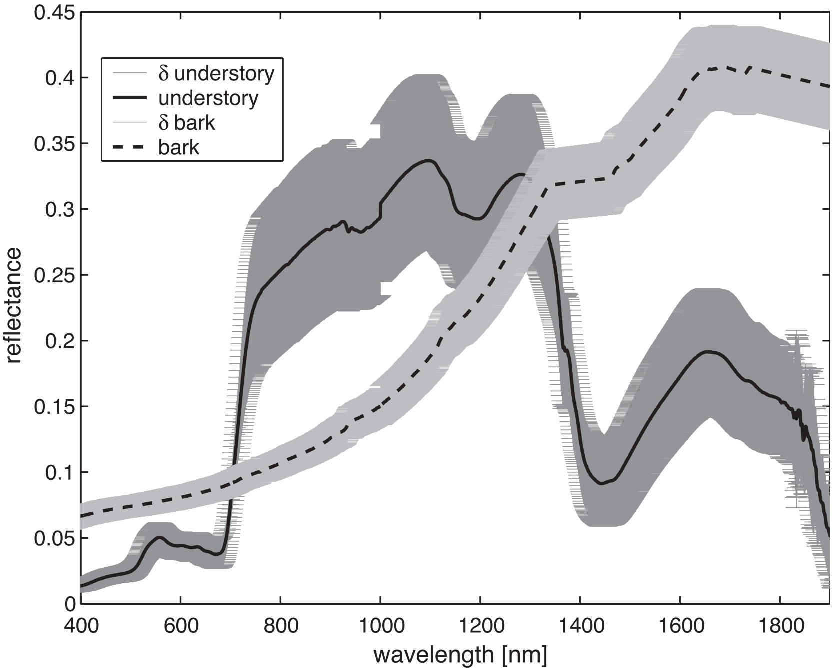


Fig. 2. Reflectance of the canopy components understory and bark representing the spectral properties of the background and the woody parts necessary for the radiative transfer parameterization. Error bars indicate the variability (one standard deviation, number of measurements: 35 understory spectra, 10 bark spectra) of the measurements.

the sun during the overflight time to minimize directional effects (Beisl, 2001). The images were geoatmospherically processed with the modules PARGE and ATCOR4 to obtain geocoded top-of-canopy reflectances (Richter & Schläpfer, 2002; Schläpfer et al., 2003; Schläpfer & Richter, 2002).

The spectroradiometric measurements of selected reference targets in the field also allowed a validation of the retrieved surface reflectance and a subsequent vicarious calibration of the imaging spectrometer data (Secker et al., 2001). The quality of the vicarious calibration and radiometric correction was assessed, taking ground spectroradiometric measurements of a homogeneous meadow as reference. The reflectance derived from the imaging spectrometer DAIS7915 yielded absolute differences relative to ground reflectance of 0.4% close to 550 nm and 0.8% in the NIR, which corresponded to 8% (550 nm), respectively, to 2% (NIR) of relative deviation. An image quality assessment at radiance level revealed a list of bad bands which were discarded from analysis, leaving a number of 34 bands in the wavelength range of 0.5 – 1.8 μm.

Mean reflectance values were calculated over an area of $30 \times 30$ m for each intensive test site, representing the canopy reflectance of the stand scene characterized by the corresponding ground measurements.

## 3. Radiative transfer modeling for canopy parameter estimation

Two well-known hybrid radiative transfer models of different complexity, GeoSAIL (Huemmrich, 2001) and FLIGHT (North, 1996), were used to describe the canopy reflectance at the scene level. A scene was here defined as an area of $30 \times 30$ m, fulfilling the assumption of the RTMs which both characterized the canopy reflectance for a scene whose components, such as crown or shadow, were small compared to the absolute modeled area. The radiative transfer at the foliage level was characterized by the model PROSPECT (Jacquemoud et al., 1996) which provided the foliage optical properties as a function of the biochemistry and is coupled to both of the employed canopy RTM. The leaf model PROSPECT was chosen due to its small number of parameters and its wide validation including the application to coniferous foliage (Kuusk & Nilson, 2000; Zarco-Tejada et al., 2004).

The relatively simple radiative transfer model GeoSAIL can describe the canopy reflectance of a complete scene including discontinuities in the canopy and shadowed scene components. The RTM combines a simple geometric model with the SAIL model (Verhoef, 1984) that provides the reflectance and transmittance of the tree crowns. The geometric model determines the fraction of the illuminated and shadowed scene components as a function of canopy coverage, crown shape, and illumination angle. All trees are assumed to be identical, with no crown overlap nor does the model account for mutual shading. The radiative transfer within the crowns is calculated using SAIL which considers the canopy as a horizontal, homogeneous, turbid, and infinitely extended vegetation layer composed of Lambertian scatterers. The SAIL version within GeoSAIL is adapted to account for the contribution of multiple canopy components with different optical properties, leaf area index, and foliage inclination angles but is limited to 10 wavelength bands. For the coupling of GeoSAIL with PROSPECT, a SAIL version (Weiss et al., 2001) capable of dealing with an unlimited number of bands and multiple canopy components, such as foliage and branches, was implemented. Subsequently, we discriminate between the initial GeoSAIL model and the here-adapted GeoSAIL version.

FLIGHT is a three-dimensional ray-tracing model using Monte Carlo techniques for the radiative transfer within crown boundaries and deterministic ray tracing between the crowns and other canopy components. The canopy structure is represented by geometric primitives defined by the crown shape and size, tree height, position, and distribution. Contrary to GeoSAIL, the geometric representation of FLIGHT deals explicitly with crown overlapping, mutual shading, and multiple scattering between crowns. Each crown is assumed to be homogeneous, characterized by its structural variables as well as by its foliage optical properties. The characterization of the crown may vary for each tree. FLIGHT calculates directional reflectance by accumulating photons in predefined solid view angles. The precision of the simulated reflectance ($\delta_{\mathrm{FLIGHT}}$) is directly related to the number of viewing angles ($n_\Theta$, number of zenith angles; $n_\Psi$, number of azimuth angles) and the number of photons ($n_{\mathrm{photons}}$):

$$\delta_{\mathrm{FLIGHT}} = \sqrt{\frac{n_\Theta \cdot n_\Psi}{n_{\mathrm{photons}}}} \quad (1)$$

### 3.1. RTM parameterization and error propagation

Canopy reflectance at the scene level was simulated by the two selected canopy radiative transfer models coupled with the leaf model PROSPECT. The radiative transfer was parameterized at the foliage and canopy level by the average field data of the four core test sites describing the biochemical and biophysical properties of the canopy (Table 1).

The input parameters describing the foliage biochemistry as required by PROSPECT were provided by ground measurements. The mesophyll structure parameter $N$ was inverted by iterative minimization of PROSPECT from the average foliage reflectance measured with the Licor1800 integrating sphere, while the biochemistry was set to stand values. Uncertainty of the $N$ parameter estimation was assessed by inversion over the variability of foliage reflectance measurements. The foliage reflectance showed a high variability due to errors in the assessment of gaps within the observed foliage sample. Consequently, the $N$ parameter was subject to an uncertainty of 22%. The spectral properties of the remaining canopy components such as the understory and woody parts were characterized by ground spectroradiometric measurements and were assumed to be inherent to all test sites (Fig. 2). Woody parts were treated as opaque foliage elements thus only reflecting or absorbing incident radiation. The structural parameterization within the crown relied on the total LAI of the overstory, corrected for clumping effects. The derived wood fraction allowed resolving the total overstory LAI into its green foliage and woody parts. The average inclination angle could be parameterized separately for the two foliage elements in GeoSAIL; spherical distribution for green foliage; and plagiophile distribution for woody parts. FLIGHT parameterization assumed both elements to be spherically distributed because no separate treatment was possible. The tree geometry relevant within the respective RTM was based on the forest stand characteristics describing tree height, crown radius, and crown length. Trees were horizontally distributed within the scene according to a Poisson distribution.

Uncertainties in the radiative transfer parameterization introduced by the measurements and the related instrument errors were included in the model simulations represented by the relative standard error for each parameter (Table 1). Standard error propagation was applied assuming linear independency of the input parameters to assess the effect of ground data uncertainties on canopy reflectance (ISO, 1995). An approximation of the accuracy of canopy reflectance simulated by FLIGHT (relative standard error of 1.9% for the settings: 1 million photons, 19 zenith and 72 azimuth angles) as a function of the photon number was also included in the error propagation. For GeoSAIL, no approximation of the model accuracy was needed due to the analytical nature of the model. Uncertainties related to the assumptions within the radiative transfer representation made by the models were not accounted for.

### 3.2. Inversion of GeoSAIL

Due to its low computational costs and its comparable performance to FLIGHT (Fig. 3), GeoSAIL was chosen for the estimation of canopy variables by model inversion. The inversion of GeoSAIL was based on lookup tables (LUT), that were generated by precomputing the canopy reflectance for 130,000 canopy realizations while considering the measurement configuration. The parameters corresponding to each canopy realization were randomly drawn following a uniform distribution. The range of each variable was defined based on ground measurements performed in this study and on experimental data presented in literature (Ceccato et al., 2001; Chen et al., 1997b; Dungan et al., 1996; Gond et al., 1999; Table 2). The selected ranges corresponded to a distribution of the respective variable typical for the observed coniferous canopy. Consequently, the generation of the LUT allowed for the implementation of general prior information depending on the specific vegetation type. Tree geometry and spectral properties of the understory and

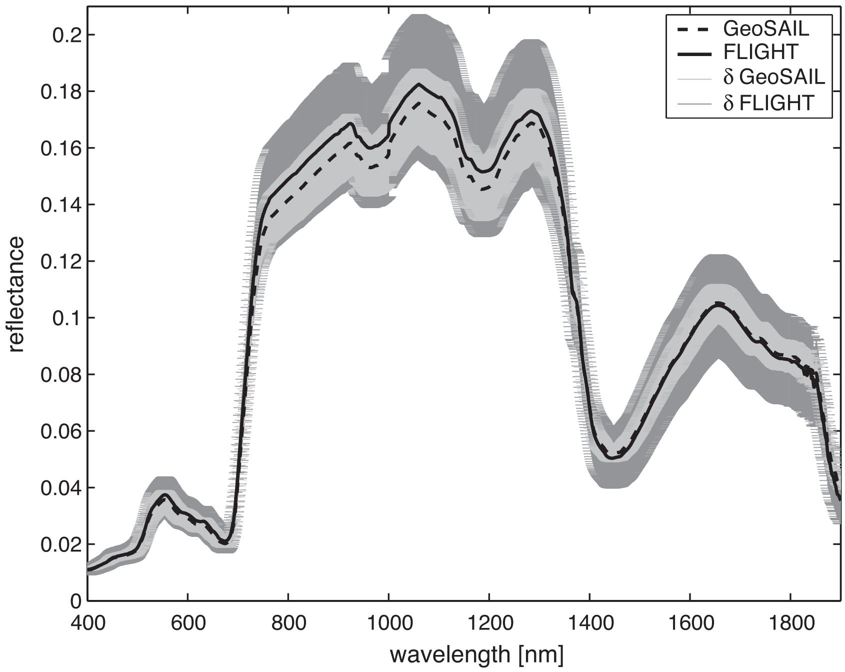


Fig. 3. Comparison of simulated canopy reflectance by GeoSAIL and FLIGHT for the core test site LWF1, including their respective uncertainties ($\delta_{\mathrm{GeoSAIL}}$, $\delta_{\mathrm{FLIGHT}}$). The root-mean-square error over the whole wavelength range amounted to 0.9% reflectance.

Table 2
Specific ranges for each parameter describing the space of canopy realizations for the generation of the lookup table

| RTM parameter | Unit | Minimum | Maximum |
|---|---|---|---|
| LAI | unitless | 1 | 5 |
| Fractional cover | % | 0.4 | 0.85 |
| Wood fraction | % | 0.25 | 0.45 |
| Chlorophyll content | μg/cm$^2$ | 55 | 80 |
| Water content | g/cm$^2$ | 0.025 | 0.065 |
| Dry matter | g/cm$^2$ | 0.02 | 0.05 |
| N | unitless | 2 | 5 |

woody parts were specified by the forest stand characteristics and ground measurements.

The model inversion was carried out by minimizing the merit function $\chi^2$, defined as the distance between the canopy reflectance $\rho_{\mathrm{mes}}$, acquired by the DAIS7915, and the simulated reflectance $\rho_{\mathrm{sim}}$ found in the LUT. The distance criterion was weighted using the uncertainty of the spectroradiometric measurements $\delta_{\mathrm{DAIS}}$ related to calibration of the DAIS sensor and the atmospheric correction of the imaging spectrometer data.

$$\chi^2 = \sum_{i=1}^{n_\lambda} \frac{1}{\delta^i_{\mathrm{DAIS}}} \left(\rho^i_{\mathrm{mes}} - \rho^i_{\mathrm{sim}}\right)^2 \tag{2}$$

where $n_\lambda$ is the number of finally included imaging spectrometer bands. Canopy realizations found within a tolerance of 20% of the minimal calculated distance $\chi^2$ were considered as possible solutions; their median defined the final solution, and their standard deviation, the uncertainty of the inversion.

## 4. Results and discussion

A prerequisite of the proposed radiative transfer modeling approach was to determine the validity of the chosen models for the representation of the radiative transfer within the complex forest structure. Precise and comprehensive canopy parameterization of the radiative transfer models enabled a comparison of simulated canopy reflectance with actual canopy reflectance acquired by the imaging spectrometer as well as an intercomparison of the two presented models.

Despite the different nature of the two radiative transfer models and their significant different levels of complexity to represent the canopy structure, they performed comparably (Fig. 3). Relative deviation amounted up to 20% for certain wavelength ranges of low reflectance. In general, however, relative deviations were around 5%. Absolute deviation showed only a small offset between model simulations as the root-mean-square error over all wavelengths of below 1% reflectance demonstrated. It could thus be concluded that canopy reflectance characterized by the two models matched well within their respective uncertainties.

Forward simulations of canopy reflectance with GeoSAIL also demonstrated the ability of the RTM to scale-up canopy variables from the foliage to the canopy level, characterizing canopy reflectance within model and measurement uncertainties (Fig. 4). The measured canopy reflectance was well represented in the near infrared for all observed stand densities. In the visible and above 1500 nm, canopy reflectance was overestimated for higher canopy densities, as observed at sites STA1 and STA2. The imaging spectrometer

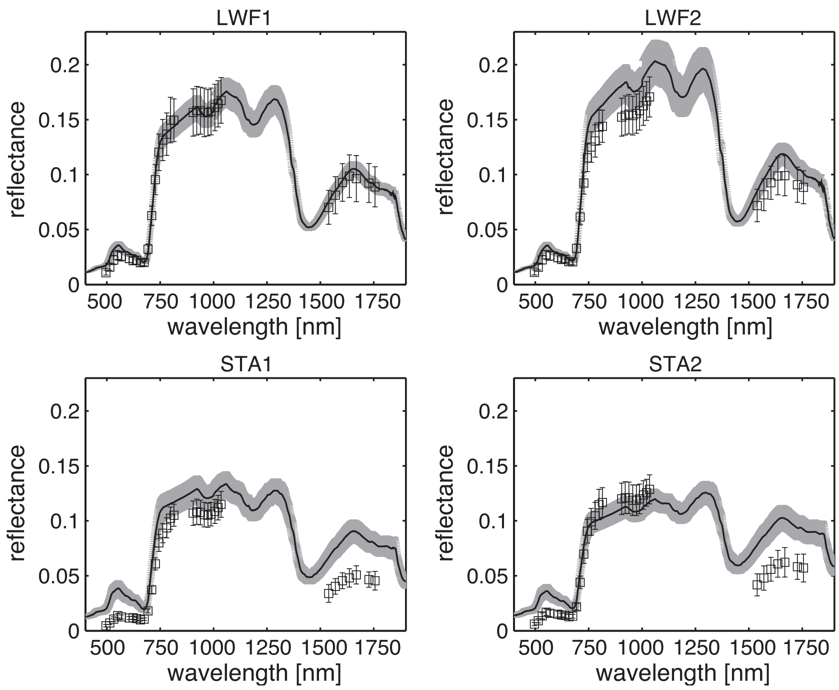


Fig. 4. Simulated (GeoSAIL) and measured canopy reflectance of the four core test sites. Error bars represent the uncertainties of the RTM approach (solid grey) and of the DAIS measurements including errors of radiometric correction and spatial variability (black squares with error bars).

ROSIS showed significantly higher reflectance in the visible than the investigated DAIS data, indicating calibration problems especially for low reflectance values. The effects could be also attributed to mutual shadowing effects which were not accounted for by the GeoSAIL radiative transfer representation although FLIGHT showed similar behavior. It should also be stated here that low signal to noise ratio (SNR) for wavelengths above 1.8 μm prevented the use of these bands specifically sensitive to leaf water content. Modern imaging spectrometers like AVIRIS, Hymap, and APEX are able to provide more stable and reliable data improving especially the capability of foliar biochemistry estimation (Cocks et al., 1998; Green et al., 1998; Schaepman et al., 2003). In addition, the potential of fuel properties mapping with spaceborne imaging spectrometers has been shown for the case of Hyperion, although the low SNR and image artifacts of the Hyperion data limited its use for the estimation of fuel moisture (Roberts et al., 2003; Ustin et al., 2002). The effect of uncertainties of the canopy parameterization on canopy reflectance was considered using standard error propagation. Main error sources were the uncertainties connected to the measurements of the LAI and the fractional cover, as well as the mesophyll structure parameter. These parameters, difficult to determine in the field, were already measured with important errors and propagated efficiently through the radiative transfer and affected the canopy reflectance significantly.

The forward simulation of canopy reflectance and the comparison of the selected radiative transfer models showed the potential of estimating forest canopy variables based on the relative simple and easily invertible model GeoSAIL. Inverting GeoSAIL for measured canopy reflectance subsequently

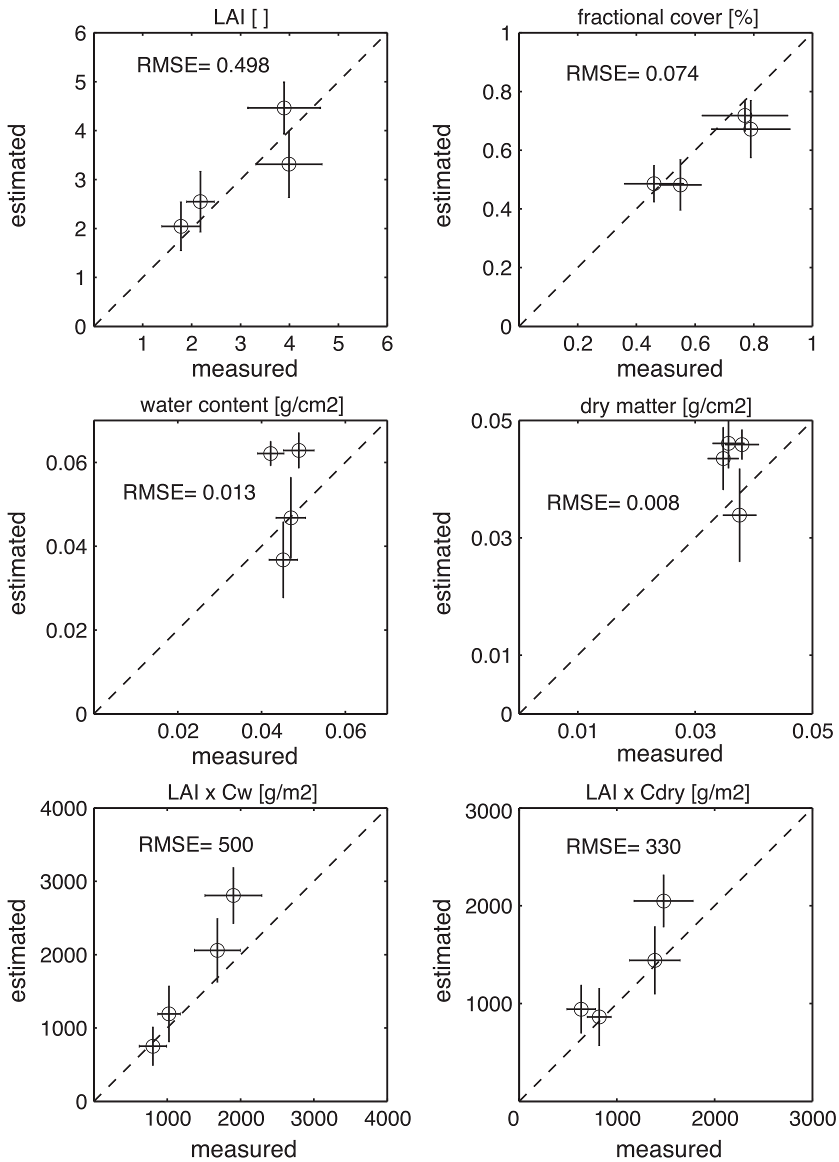


Fig. 5. Performance of model inversion: estimates and measurements of canopy parameters are presented; error bars represent the uncertainties related to the ground measurements and model inversion, respectively (LAI × Cw, canopy water content; LAI × Cdry, canopy dry matter content).

assessed the feasibility of estimating canopy variables employing a radiative transfer model. Fig. 5 presents the results of the forest variable estimation relative to the ground measurements of the respective variable, while also indicating the uncertainties associated to the inversion process and ground measurements. The model inversion performed well with reasonable root-mean-square errors and within uncertainties for the variables describing the canopy structure such as LAI and fractional cover. The estimation of the foliage variables presented less-stable results, but the average accuracy of estimates still amounted to 71.6% and 78.2%, respectively, for foliage water content and dry matter. The estimation of chlorophyll foliage content showed poor results probably due to the effects in the visible already observed and discussed for the simulated canopy reflectance. A limitation was caused by the variation of foliage variables, which was not sufficiently large for a thorough validation due to the observed canopy homogenous in terms of specie, phenology, and environmental conditions. Gond et al. (1999) presented seasonal observations of biochemical and biophysical parameters, which showed for evergreen species, e.g., *Pinus sylvestirs* L., a similar, rather stable temporal evolution. Leaf water content increased by 10% in spring due to bud burst and LAI did not vary significantly over the season. For the observed forest stand in this study, the spatial variation of the canopy structure can be consequently regarded as the most significant source of variability relevant for the canopy fuel properties.

The 120–128.9% FMC we observed in this study is similar to FMC values of 95–146% observed for a burnt canopy of Lodgepole pine (*Pinus contorta*) in the Yellowstone National Park, suggesting considerable fire risk for the Swiss National Park (Hartford & Rothermel, 1991). The product of LAI and foliage water or dry matter content represented the canopy content of the respective biochemical constituent which could present an additional quantity most relevant to the inflammability and the combustion of forests (Ceccato et al., 2002a). The derived LAI along with the wood fraction of the canopy could serve as indication of the amount and quality of biomass available to combustion. The estimates of the canopy characterization could finally define site-specific physical descriptions of fuel types necessary for the initialization of forest behavior models such as FARSITE (Finney, 1998; Miller & Yool, 2002).

## 5. Conclusion

The estimation of crown forest fire fuel properties by radiative transfer modeling was successfully demonstrated for a heterogeneous canopy like a conifer forest. The coupled radiative transfer models, PROSPECT and GeoSAIL, exploited efficiently canopy reflectance acquired by imaging spectrometry to assess quantitatively and independently the canopy structure, as well as the foliage water content of the observed forest. Both canopy variables provided information on the vegetation status vital to the management of forests with respect to possible wildland fires. The hyperspectral extension of GeoSAIL supported the robustness and reliability of the combined assessment of biophysical and biochemical variables.

An important step within this study was the validation of two radiative transfer models of different complexity for the proposed application. A field campaign provided comprehensive information on the canopy for the forward simulation of canopy reflectance including the measurement uncertainties. The results of the subsequent comparison of simulated and observed canopy reflectance proved the ability of both models to represent the radiative transfer within a heterogeneous canopy independently of the model complexity. Both radiative transfer models actually performed comparably simulating canopy reflectance within their own uncertainties. The implication of the similar model performances was important because it allowed us to employ the relative simple and analytical model GeoSAIL instead of the complex ray-tracing model, FLIGHT, which significantly reduced the computational cost of the model inversion. Finally, the results of the model inversion proved the ability of radiative transfer modeling to quantitatively assess the canopy variables under investigation while taking the involved uncertainties into account. The derived canopy characterization presented the actual spatial distribution of fuel properties as they occur on the landscape. The increased spatial resolution of quantitative information on fuel properties could help to increase the accuracy of fire behavior and ignition prediction.

The successful canopy variable estimation could be partly attributed to the prior information which was implicitly taken into account during the generation of the lookup table with site-specific model parameter ranges derived from experimental data. The necessary information could also be provided by ancillary information as forest inventory or by additional remote sensing data, such as provided by a LIDAR (Morsdorf et al., in press; Riano et al., 2003). Besides, more stable imaging spectrometer data, supplementary information on canopy structure identified as the major source of uncertainty when characterizing canopy reflectance by radiative transfer models, would be helpful to improve the performance of the presented approach. Consequently, the geometrical representation of the canopy by a LIDAR system would offer an optimal complement to the radiometric information. Future research will also focus on a suitable inversion technique for the optimal introduction of ancillary information into the retrieval algorithm.

## Acknowledgements

This project is funded by the EC project 'Forest Fire Spread and Mitigation (SPREAD), EC-Contract Nr. EVG1-CT-2001-00027, and the Federal Office for Education and Science of Switzerland (BBW), BBW-Contract Nr. 01.0138.

Ground measurements and acquisition were supported by RSL staff, WSL (tree sampling), and INRA (leaf optical measurements). Thanks to the authors of the different radiative transfer models used in this study for providing their code.

The airborne operations have been carried out in the framework of the EU Access to Infrastructure project HYSENS, under guidance of DLR. The access permission and support of field logistics has been given by the SNP.

The numerous and helpful comments of the two anonymous reviewers are thankfully acknowledged.

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# Second Publication

## Inversion of a LIDAR Waveform Model for Forest biophysical Parameter Estimation

Koetz, B., Morsdorf, F., Sun, G., Ranson, K.J., Itten, K., & Allgöwer, B. (2006). Inversion of a LIDAR Waveform Model for Forest biophysical Parameter Estimation. *IEEE Geosciences and Remote Sensing Letters*, 3, 49-53

IEEE GEOSCIENCE AND REMOTE SENSING LETTERS, VOL. 3, NO. 1, JANUARY 2006 49

# Inversion of a Lidar Waveform Model for Forest Biophysical Parameter Estimation

B. Koetz, *Student Member, IEEE*, F. Morsdorf, G. Sun, *Senior Member, IEEE*, K. J. Ranson, K. Itten, *Senior Member, IEEE*, and B. Allgöwer

***Abstract*—Due to its measurement principle, light detection and ranging (lidar) is particularly suited to estimate the horizontal as well as vertical distribution of forest structure. Quantification and characterization of forest structure is important for the understanding of the forest ecosystem functioning and, moreover, will help to assess carbon sequestration within forests. The relationship between the signal recorded by a lidar system and the canopy structure of a forest can be accurately characterized by physically based radiative transfer models (RTMs). A three-dimensional RTM is capable of representing the complex forest canopy structure as well as the involved physical processes of the lidar pulse interactions with the vegetation. Consequently, the inversion of such an RTM presents a novel concept to retrieve biophysical forest parameters that exploits the full lidar signal and underlying physical processes. A synthetic dataset and data acquired in the Swiss National Park (SNP) successfully demonstrated the feasibility and the potential of RTM inversion to retrieve forest structure from large-footprint lidar waveform data. The SNP lidar data consist of waveforms generated from the aggregation of small-footprint lidar returns. Derived forest biophysical parameters, such as fractional cover, leaf area index, maximum tree height, and the vertical crown extension, were able to describe the horizontal and vertical forest canopy structure.**

***Index Terms*—Biophysical parameters, fcover, inversion, leaf area index (LAI), light detection and ranging (lidar) waveform, three-dimensional (3-D) model, tree height.**

## I. Introduction

CANOPY structure, both in horizontal and vertical dimension, is a key factor for the functioning of forest ecosystems. The dispersion and number of canopy elements within the three-dimensional (3-D) space directly controls the exchange and fluxes of energy and mass between vegetation and atmosphere [1]–[3]. The major physiological processes of vegetation including photosynthesis (over the scattering and absorption of incoming radiation) and evapotranspiration are influenced by the biophysical forest parameters that describe the canopy structure. Moreover, the quantification of canopy structure allows for the assessment of the above-ground biomass, which in turn indicates the above-ground carbon stock of the observed forest.

Remote sensing can provide spatially continuous observations of biophysical vegetation parameters for regional to global ecosystem studies in order to define realistic initial and boundary conditions of ecological models. The remote sensing technique light detection and ranging (lidar) is particularly suited to derive information about biophysical parameters such as tree height, fractional vegetation cover, canopy geometry, and above-ground biomass. A number of studies have shown the sensitivity of small- and large-footprint lidar systems relative to forest canopy structure with unprecedented accuracy [4]–[8]. The measurement principle of lidar relies on laser pulses propagating vertically through the canopy, while scattering events with the vegetation are recorded as function of time. The response obtained by lidar is consequently dependent on the vertical distribution of canopy elements such as the foliage, branches, and trunks, as well as the underlying terrain [9].

However, for the retrieval of forest parameters based on lidar data, the interaction of the laser with the complex 3-D canopy structure has to be adequately understood and interpreted. For this purpose, several radiative transfer models (RTMs) have been developed, incorporating a realistic forest stand representation, lidar sensor specifications, and the involved physical processes [10]–[12]. The inversion of such a physically based model provides a novel concept of retrieving biophysical parameters from lidar data in a robust and quantitative manner.

In this study, we propose to invert a 3-D lidar waveform model [12] to estimate tree height, fractional cover, and overstory leaf area index (LAI) of a coniferous forest. The invertibility and general potential for parameter retrieval of the model are first tested on a synthetic dataset. The performance of the proposed approach is further validated on an actual dataset of field measurements and lidar waveforms generated from small-footprint lidar returns.

## II. LIDAR Waveform Model

A 3-D waveform model was used to simulate lidar waveforms as a function of forest stand structure and sensor specifications [12]. The model constructs a 3-D representation of the observed forest stand taking into account the number and position of trees, crown geometry and shape, tree height, and underlying ground topography (Fig. 1). The crown itself is described as a turbid scattering medium parameterized by its foliage area volume density, the Ross–Nilson G-factor [13], and the foliage reflectance. Finally, the ground reflectance needs to be defined for an accurate waveform simulation.

Manuscript received March 15, 2005; revised July 5, 2005. This project was supported in part by the European Commission (EC) project "Forest Fire Spread and Mitigation (SPREAD)" under EC-Contract EVG1-CT-2001-00027 and in part by the Federal Office for Education and Science of Switzerland (BBW) under BBW-Contract 01.0138.

B. Koetz, F. Morsdorf, and K. Itten are with the Remote Sensing Laboratories, University of Zurich, CH-8057 Zurich, Switzerland (e-mail: bkoetz@geo.unizh.ch).

G. Sun is with the Department of Geography, University of Maryland, College Park, MD 20742 USA.

K. J. Ranson is with the Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

B. Allgöwer is with the Geographic Information Systems, University of Zurich, CH-8057 Zurich, Switzerland.

Digital Object Identifier 10.1109/LGRS.2005.856706

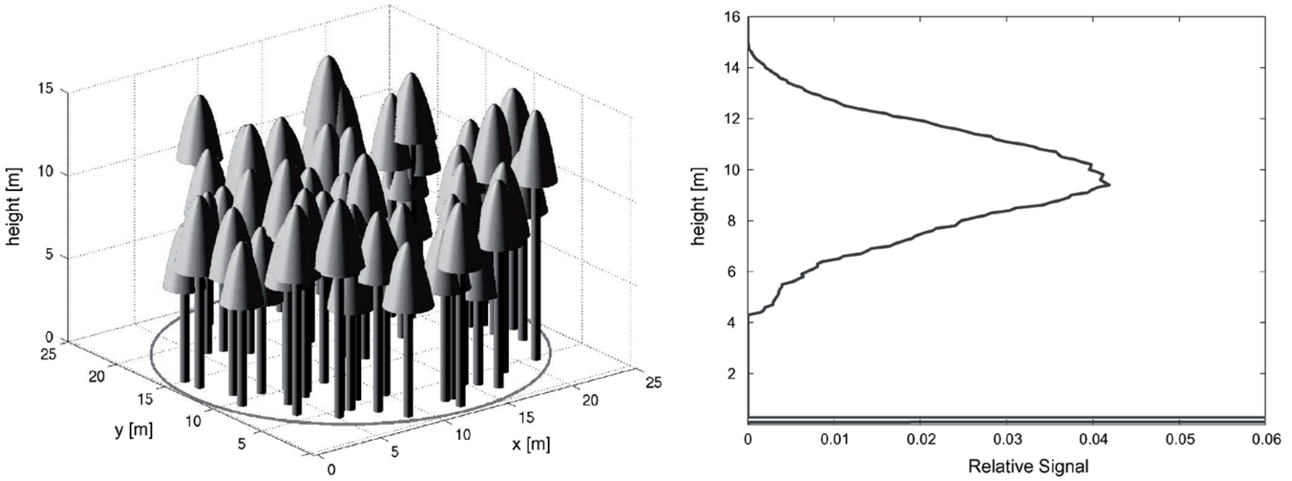


Fig. 1. Example of a 3-D forest stand representation for waveform simulations, parameterization: 60 trees, maximum tree height: 15 m; crown length: 4 m; crown width: 3 m; crown shape: hemi-ellipsoid; LAI: 2.5; G-factor: 0.5; leaf reflectance: 0.215; background reflectance: 0.152; footprint: 25 m.

Within this study, the original version of the waveform model was adapted to allow for the input of LAI instead of the foliage area volume density. The updated model also calculates the fractional cover of the respective 3-D stand representation used for the waveform simulation.

## III. Data

A synthetic and an actual dataset, both comprising lidar waveforms and their corresponding canopy parameters, were available to validate the retrieval performances of the proposed approach.

### A. Synthetic Dataset

A synthetic dataset was generated by simulating the lidar waveform response of 100 artificial forest stands using the above-described lidar waveform model. The stand parameters were chosen randomly within the ranges defined in Table II, creating an independent dataset for the validation of the proposed model inversion. Details of the model parameterization are described in Section IV. Uncertainties related to errors associated to the sensor and data processing could not be taken into account because of their insufficient characterization.

### B. Swiss National Park Dataset

A field dataset was acquired over a study area located in the Eastern Ofenpass Valley, which is part of the Swiss National Park (SNP). Ofenpass represents an inner-alpine valley at an average altitude of about 1900 m a.s.l with an annual precipitation of 900–1100 mm. The south-facing Ofenpass forests, the location of the field measurement, are largely dominated by mountain pine (*Pinus montana ssp. arborea*).

Four core test sites were sampled intensively for their biophysical and spectral canopy characteristics. The sites were selected following a stratified sampling scheme to cover different canopy densities within the observed stand. Each site was defined by nine sampling points, evenly spaced in a grid of 10 m, covering a square area of 20 × 20 m. The LAI-2000 plant canopy analyzer was used to estimate the two canopy variables: LAI and fractional cover. LAI measurements were converted from effective to actual LAI values by correcting for clumping effects at the shoot and crown level [14]. The definition of LA1 used in this study is one half the total leaf area per unit ground surface area. Fractional cover was derived from the gap fraction recorded by the LAI-2000 inner ring ($\pm 13^\circ$). The spectral properties of several canopy elements including the reflectance of foliage, branches, and understory were measured with an ASD field spectrometer. For a more comprehensive description of the field measurements refer to Kötz *et al.* [15]. Forest stand measurements of the Long-term Forest Ecosystem Research Programme (LWF) of the Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL) described the basic geometric primitives of the canopy [16]. Tree height, crown radius, stem diameter, and location were measured within this program over an area of 2 ha comprising a number of more than 2000 trees with diameter at breast height larger than 0.12 m. Tree heights of single trees were extracted corresponding to respective footprints of the lidar system over the area characterized by field measurements.

An airborne lidar survey was carried out in October 2002 over the test site in the SNP with a nominal height above ground of 500 m [8]. The FALCON II sensor, a small-footprint pushbroom laser altimeter operated by the TopoSys company, was used [17]. The system provided both first and last reflection of the laser signal (first/last pulse) in a point density of more than 20 points/m$^2$ with a footprint size of about 50 cm in diameter. The FALCON II sensor operates at a wavelength of 1560 nm. The raw laser signals were transformed to above-ground heights by subtraction of interpolated ground heights derived from the digital terrain model (DTM) produced by TopoSys. The horizontal positional and the vertical accuracy of the DTM amounted to 0.5 and 0.15 m, respectively.

The single-pulse data of the small-footprint lidar were converted into digitized waveforms following the approach described in [18]. The lidar return waveform was modeled as the sum of reflections within a footprint of 25 m in diameter. Instrument-specific characteristics have been taken into account emulating the specifications of the large-footprint lidar system

TABLE I
INSTRUMENT SPECIFICATIONS FOR LVIS WAVEFORM EMULATION, ADAPTED FROM [18]

| *Parameter* | *unit* | *value* |
|---|---|---|
| Footprint | m | 25 |
| Along-beam laser intensity half-width ($\sigma_p$) | m | 0.6893 |
| Across-beam laser intensity half-width ($\sigma_f$) | m | 6.25 |
| Bin width | m | 0.1 |
| Gaussian kernel half-width ($\sigma$) | m | 0.6893 |

TABLE II
PARAMETER RANGES AND DISTRIBUTION DESCRIBING THE GENERATION OF THE LUT. ADDITIONAL PARAMETERS WERE FIXED TO DEFAULT OR FIELD MEASUREMENT VALUES: FOLIAGE REFLECTANCE ($\lambda$: 1560 nm): 0.215, BACKGROUND REFLECTANCE ($\lambda$: 1560 nm): 0.152, CROWN SHAPE: HEMI-ELLIPSOID, G-FACTOR: 0.5, AND TREE NUMBER: 60

| *Parameter* | *unit* | *Min* | *Max* | *Distribution* |
|---|---|---|---|---|
| max. Tree height | m | 8 | 18 | uniform |
| Crown length | m | 2 | 6 | uniform |
| Crown width | m | 1 | 5 | weighted |
| LAI | [$m^2/m^2$] | 1 | 4 | uniform |
| Fractional cover[a] | % | 0.09 | 0.95 | uniform |

a. No direct model input parameter but calculated for each canopy realization

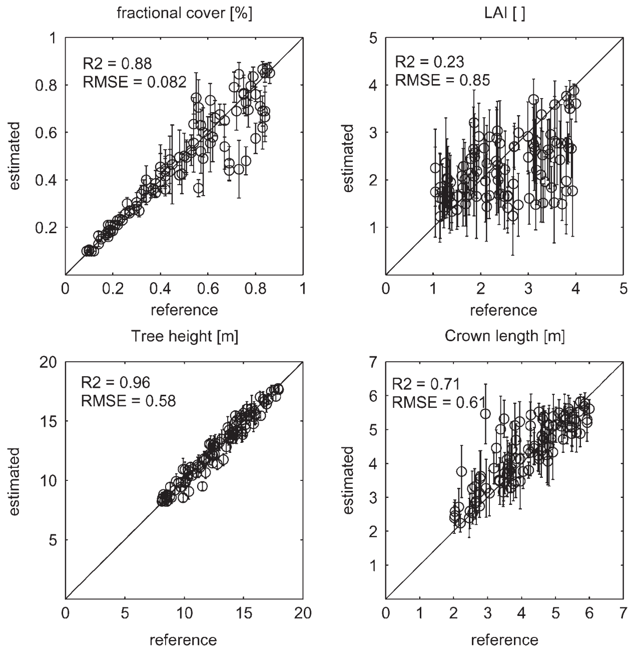


Fig. 2. Performance of the model inversion for the synthetic dataset. Circles represent the median of possible solutions, and error bars represent the uncertainties related to the model inversion (standard deviation of possible solutions).

Laser Vegetation Imaging Sensor (LVIS) (Table I) [19]. Subsequently, the waveforms were normalized to their maximum peak (the ground signal) and convoluted by a Gaussian kernel. Only relevant waveforms of footprints corresponding to the field measurements were extracted and further investigated during this study.

## IV. INVERSION OF WAVEFORM MODEL

The inversion of the lidar waveform model was based on a lookup table (LUT) approach. A LUT model inversion is comprised of two parts: the generation of the LUT itself and the selection of the solution that corresponds to a given measurement.

A comprehensive LUT was generated by simulating lidar waveforms for a total number of 100 000 canopy realizations, while considering the sensor configuration. For each of these canopy realizations, a forest stand representation had to be constructed following the respective input parameters of the waveform model. The input model parameters were sampled randomly within defined ranges and followed generally a uniform distribution (Table II). The uniform distribution of the sought parameter fractional cover was approximated by a weighted distribution of crown width samples. The selected parameter ranges corresponded to their natural occurrence typical for the observed canopy type. A number of model parameters were fixed to values partly retrieved from field measurements (Table II). The foliage and background reflectance were provided by spectrometric measurements, and the crown shape was approximated as a hemiellipsoid. Both the G-factor and the number of trees were fixed because a higher total number of model parameters and their intercorrelation increase the generally ill-posed nature of a model inversion [20]. The G-factor was set to the value of 0.5 representing a spherical foliage distribution typical for conifers. The absolute number of trees within a forest stand was not a direct subject of interest and could thus be set the approximate average tree density in the observed stand (60 trees per footprint). Tree positioning within the lidar footprint was both randomly and uniformly distributed. However, the heights of individual trees followed a normal distribution offset by the assigned maximum tree height for a realistic stand reconstruction. The terrain was assumed to be flat since terrain variations were already taken into account before the waveform conversion.

The solution of the model inversion was found by minimizing the merit function $(\chi^2)$, defined as the distance between the reference waveform $(\omega_{\mathrm{ref}})$ acquired by the lidar system and the simulated waveform $(\omega_{\mathrm{sim}})$ found in the LUT. Simulated waveforms were normalized relative to their maximum peak for conformity with the measured signal

$$\chi^2 = \sum_{i=1}^{n_{\mathrm{bin}}} \left(\omega_{\mathrm{ref}}^i - \omega_{\mathrm{sim}}^i\right)^2 \tag{2}$$

where $n_{\mathrm{bin}}$ is the number of bins of the digitized waveform. However, given the ill-posed nature of a model inversion caused by measurement and model uncertainties, model inversion generally leads to a range of equally possible solutions [21]. Thus, the LUT was sorted accordingly to the merit function $(\chi^2)$, and the first ten canopy realizations (those with the minimal $\chi^2$) were considered as possible solutions. The median of the possible solutions defined the final solution and their standard deviation the uncertainty of the inversion.

## V. RESULTS AND DISCUSSION

The feasibility of the proposed parameter estimation by inversion of a waveform model has been tested and validated on two different datasets. A synthetic dataset showed first the general invertibility of the model and the parameter potentially deducible. Furthermore, a realistic dataset acquired over the Swiss

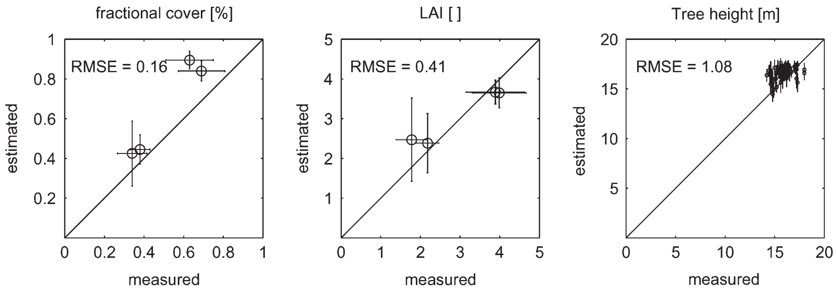


Fig. 3. Performance of the model inversion for the SNP dataset. Circles represent the median of possible solutions, and error bars represent the uncertainties related to the field measurements and model inversion (standard deviation of possible solutions).

National Park assessed the actual retrieval performance of specific biophysical forest parameters.

### A. Synthetic Dataset

In the case of the synthetic dataset, all estimated parameters but the LAI were retrieved with significant correlation coefficients $(R^2)$ and reasonable root mean square errors (RMSEs) (Fig. 2). The results of estimated LAI showed basic difficulties for the proposed retrieval of this particular parameter. High LAI within sparse canopies, i.e., with fractional cover smaller than 0.25, were systematically underestimated. Fractional cover was well estimated, but showed an increasing scatter for higher values. The increased spread was probably caused by tree clumping and consequent crown overlapping for stands with higher fractional cover. Varying degrees of crown overlapping can cause multiple waveform responses for stands with the same fractional cover, thus leading to ambiguities within the retrieval process. Also, some cases of underestimations were due to compensation by high LAI. The results of estimated crown length showed significant correlation to their reference values. However, a rather high spread over the whole parameter range could be observed. This observation is most likely due to the waveform's higher sensitivity to the actual vertical extension of the crown layer than its sensitivity to the crown length. The vertical extension of the crown layer is not only defined by the crown length but also by the varying height of single trees. Finally, the maximum tree height of each observed forest stand was well estimated with a significant correlation coefficient of above 0.9 and low RMSE.

### B. Swiss National Park Dataset

Airborne lidar data and field measurements acquired in the Swiss National Park allowed for the estimation and subsequent validation of forest parameters including fractional cover, LAI, and maximum tree height. Unfortunately, no precise field measurements were available for the vertical crown extent.

Estimation of the studied parameters agreed well with the field measurements, revealing results close to the 1 : 1 line (Fig. 3). The number and, in the case of tree height, variability of the field measurements did not allow for a statistical evaluation. The fractional cover results were systematically overestimated probably due to the geometric representation of trees within the waveform model. The simple geometric shapes characterizing the tree crowns in the model neglect gaps within the crowns, thus leading to an overestimation of fractional cover. Despite the unfavorable results observed for the synthetic dataset, LAI could be estimated within the uncertainties of the field measurements and inversion algorithm. High LAI in the field were only observed within closed canopies avoiding the retrieval difficulties apparent in the synthetic data. Validation of the maximum tree height retrieval was limited by the low variability of the field measurements. Still, estimated tree height agreed well with the field measurements except for a systematic overestimation. This overestimation was due to a vertical extrapolation of the waveform caused by the Gaussian convolution performed during the large-footprint lidar data processing.

## VI. Conclusion

The response of a large-footprint lidar over a forest canopy is governed by the complex forest structure and the involved physical processes. Consequently, a physically based radiative transfer model is an appropriate method to interpret and exploit the waveform recorded by such a system. Two separate datasets successfully demonstrated the potential of RTM inversion to retrieve horizontal and vertical forest structure from lidar data.

A synthetic dataset verified the invertibility of the proposed waveform model for forest parameters retrieval. Horizontal and vertical forest structure expressed as fractional cover, maximum tree height, and vertical extension of the crown layer could be estimated. LAI of the forest overstory was only retrievable for the coniferous canopy studied in the SNP. Estimates of fractional cover and maximum tree height could also be successfully validated with the *in situ* field data. However, model assumptions and data processing difficulties limited the accuracy of the obtained results. Model development and the use of waveform data obtained by a dedicated large-footprint sensor will further improve the retrieval performance. Although measured large-footprint lidar data will introduce new problems to the algorithm including the effect of varying terrain and laser illumination within the footprint.

Due to its physically based nature of the proposed concept and algorithm, there is no dependency on *in situ* calibration. However, it relies on ancillary information such as crown shape and both foliage and background reflectance. Imaging spectroscopy can provide spectral information on the relevant canopy components and can help to define the crown shape or G-factor by detecting the observed forest type. Consequently the combination of the two different sensor types, lidar and imaging spectrometers, could improve the stability and accuracy of the proposed forest parameters retrieval.


## ACKNOWLEDGMENT

This study is partly based on a research visit to the Biospheric Sciences Branch at the National Aeronautics and Space Administration Goddard Space Flight Center, which was only possible with the support of E. Middelton, P. E. Campbell, and K. J. Ranson.

Tree height measurements were provided by the Long-term Forest Ecosystem Research Programme, a partnership between the Swiss Federal Institute of Forest, Snow, and Landscape Research and the Swiss Federal Institute of Environment, Forest, and Landscape SAEFL.


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# Third Publication

## Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization

Koetz, B., Sun, G., Morsdorf, F., Ranson, K.J., Itten, K., & Allgöwer, B. (2006). Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization. *Remote Sensing of Environment*, submitted

# Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization

Benjamin Koetz[1], Guoqing Sun[2], Felix Morsdorf[1], K. J. Ranson[3], Mathias Kneubühler[1], Klaus Itten[1] and Britta Allgöwer[4]

[1]Remote Sensing Laboratories (RSL), Dept. of Geography, University of Zürich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland, bkoetz@geo.unizh.ch

[2] Department of Geography, University of Maryland, College Park, MD 20742 USA

[3]Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA

[4]Geographic Information Systems, Dept. of Geography, University of Zürich

## Abstract

A comprehensive canopy characterization of forests is extracted from the combined remote sensing signal of imaging spectrometry and large footprint LIDAR. The inversion of two linked physically based radiative transfer models (RTM) provided the platform for exploiting synergistically the specific and independent information dimensions obtained by the two earth observation systems. Due to its measurement principle, LIght Detection And Ranging (LIDAR) is particularly suited to assess the horizontal and vertical canopy structure of forests, while the spectral measurements of imaging spectrometry are specifically rich on information for biophysical and –chemical canopy properties. In the presented approach, the specific information content inherent to the observations of the respective sensor was not only able to complement the canopy characterization, but also helped to solve the ill-posed problem of the RTM inversion. The performance of the RTM inversion has been validated on a synthetic but nevertheless realistic data set generated by a forest growth model for a wide range of forest stands. Robust estimates on forest canopy characteristics were achieved, ranging from maximal tree height, fractional cover (fcover), leaf area index (LAI) to the foliage chlorophyll and water content. The introduction of prior information on the canopy structure derived from large footprint LIDAR observations significantly improved the retrieval performance relative to estimates based solely on spectral information.

## Introduction

Vegetation controls a large part of the heat and mass fluxes within the terrestrial biosphere. The major physiological processes, such as evapotranspiration and photosynthesis, responsible within vegetation for energy and mass exchanges are driven by the canopy structure as well as the biochemistry of the foliage. For the understanding and monitoring of the typically heterogeneous and dynamic terrestrial biosphere a comprehensive and robust characterization of vegetation canopies is thus required (Sellers et al. 1997).

The vegetated land surface is often characterized by passive optical remote sensing sensors observing the spectral properties of the surface. The spectral information content is able to provide estimates on biophysical parameters, such as Leaf Area Index (LAI) and fractional cover, and on parameters related to the foliage biochemistry, such as the Fraction of Absorbed Photosynthetic Active Radiation (FAPAR) up to global scale (Myneni et al. 2002; Widlowski et al. 2001). Recently, the active optical system LIDAR started to provide information on the vertical distribution of canopy elements within a vegetation canopy (Drake et al. 2002b; Lefsky et al. 2002). While large footprint LIDAR capture the full vertical waveform over a canopy potentially form a spaceborne platform, airborne small footprint LIDAR can resolve the canopy structure up to a single tree (Harding et al. 2001; Hyyppa et al. 2001;

Morsdorf et al. 2004; Naesset 2002). The direct LIDAR observations of vertical canopy structure can thus present an independent information source complementing the spectral information content for a comprehensive canopy characterization (Gillespie et al. 2004; Hill and Thomson 2005).

The complexity of a vegetation canopy and uncertainties related to measurements and retrieval algorithm cause the vegetation characterization by remote sensing to be an ill-posed problem (Combal et al. 2003). The radiative transfer within a canopy depends on the complex 3-D canopy structure defined by the geometry, position and density of canopy elements as well as the optical properties of each canopy element (Goel and Thompson 2000). Physically based Radiative Transfer Models (RTM) have been developed to describe the interaction of radiation with the diverse canopy components at foliage and canopy level (Govaerts 1996; Jacquemoud and Baret 1990; Kuusk and Nilson 2000; Ni-Meister et al. 2001; Sun and Ranson 2000). RTM provide thus an explicit connection between canopy variables, observation and illumination geometry and the resulting remote sensing signature. Nevertheless, assumptions and number of parameters of most invertible RTM rend them to an intrinsic underdetermined system. This fact and measurement uncertainties lead to multiple possible solutions when RTM are inverted against remote sensing observations. For an improved retrieval of vegetation characteristics by RTM inversion, the number of independent information sources should thus be increased (Verstraete et al. 1996).

For the characterization of the heterogeneous canopy of a forest we propose to exploit the independent information dimensions provided by the two earth observation systems imaging spectrometry and LIDAR. While the spectral measurements of imaging spectrometry bear information on the foliar biochemical composition and only an indirect link to the canopy structure, LIDAR observations provide direct measurements of the vertical and horizontal canopy structure. The LIDAR signal, e.g. recorded as full waveform, can thus improve the accuracy and robustness of RTM inversion based solely on spectral information by reducing the uncertainties related to canopy structure. On the other hand, accurate interpretation of the LIDAR signal depends on the spectral properties of canopy elements and background. The two sensors and their information dimension are thus mutually dependent but can also complement each other.

Radiative transfer modeling of the remote sensing signals as observed by imaging spectrometry and LIDAR is described by the same basic physical processes. Consequently, an interface between two RTM based on the same physical concept and sharing common input parameters can be established. A common forest stand parameterization is used by the two models to generate a combined spectral and LIDAR waveform signature of the respective canopy. RTM inversion based on a Look Up Table (LUT) comprising the combined remote sensing signatures of imaging spectrometry and LIDAR as a function of a common forest stand parameterization offers thus a simple approach to exploit synergistically these independent information dimensions. In the presented study prior information on the canopy structure derived from the LIDAR information helps to improve the retrieval performance. Similar approaches have been promoted using prior information derived from the spatial, temporal and directional information dimension of earth observation (Atzberger 2004; Knyazikhin et al. 1998; Koetz et al. 2005; Widlowski et al. 2004).

The objective of the presented research is to develop and evaluate a methodology that fully exploits the information dimensions provided by the two earth observation systems imaging spectrometry and large footprint LIDAR to characterize a forest canopy. The exploitation of the two independent information sources ensures a robust parameter retrieval but also provides an enhanced canopy characterization, including the foliage biochemical content as well as the horizontal and vertical canopy structure. The methodology has been developed and evaluated on a synthetic but nevertheless realistic data set, which allowed for a comprehensive validation over forest stands of changing age and under different environmental conditions. The proposed approach finally also bears implications and shows potential for future multi-sensor earth observation platforms such as the proposed spaceborne mission Carbon-3D (Hese et al. 2005).

## Radiative Transfer Models

The remote sensing signatures of forest canopies as observed by an imaging spectrometer and a large footprint LIDAR have been simulated by two separate radiative transfer models (RTM). The use of the RTM has been twofold. They have been employed to generate by forward modeling an independent synthetic data set for validation purposes. Furthermore, the inversion of the two radiative transfer models provided the means for the proposed retrieval of vegetation canopy properties.

### GeoSAIL

The hybrid radiative transfer model GeoSAIL (Huemmrich 2001) describes the spectral canopy reflectance of a forest stand. The relatively simple GeoSAIL model was chosen due to its low computational costs and its comparable performance to e.g. the more sophisticated RTM FLIGHT (Kötz et al. 2004; North 1996). The radiative transfer at foliage level is characterized by the PROSPECT model (Jacquemoud and Baret 1990), which provides the foliage optical properties as a function of the biochemistry and is subsequently coupled with the canopy RTM. GeoSAIL describes the canopy reflectance of a complete scene including discontinuities in the canopy and shadowed scene components. GeoSAIL is a combination of a geometric model (Jasinski and Eagleson 1990) with the SAIL model (Verhoef 1984) that provides the reflectance and transmittance of the tree crowns. A SAIL version capable of dealing with an unlimited number of bands and multiple canopy components, such as foliage and branches, was implemented (Kötz et al. 2004). The geometric model determines the fraction of the illuminated and shadowed scene components as a function of canopy coverage, crown shape and illumination angle. All trees are assumed to be identical with no crown overlap nor does the model account for mutual shading of crowns.

### LIDAR Waveform model

A three-dimensional (3D) waveform model was used to simulate LIDAR waveforms as a function of forest stand structure and sensor specifications (Sun and Ranson 2000). The model constructs a 3D-representation of the observed forest stand taking into account the number and position of trees, tree height, crown geometry and shape as well as the exposition of the underlying topography. The crown itself is described as a turbid scattering medium parameterized by its foliage area volume density, the Ross-Nilson G-factor (Nilson 1971) and the foliage reflectance. Finally, the ground reflectance needs to be defined for an accurate waveform simulation.

Within this study the original version of the LIDAR waveform model was adapted to allow for the input of LAI instead of the foliage area volume density. The updated model also calculates the fractional cover of the respective 3D stand representation used for the waveform simulation.

## Data: Generation of synthetic data set

A synthetic but nevertheless realistic data set has been generated by linking the forest growth model ZELIG (Urban 1990) to the two radiative transfer models described above. The linked models provided a comprehensive data set of the remote sensing signatures for an imaging spectrometer and a LIDAR over a wide range of forest stands.

ZELIG simulations over time and for different sites in changing environmental settings described in detail highly variable canopy attributes, such as the canopy structure of the studied forest stands. The ZELIG forest stand descriptions were used for the parameterization of the radiative transfer models. Forward simulations of the two radiative transfer models subsequently generated the remote sensing signatures of the forest stands as observed by an imaging spectrometer and large footprint LIDAR (see Fig. 1 as example).

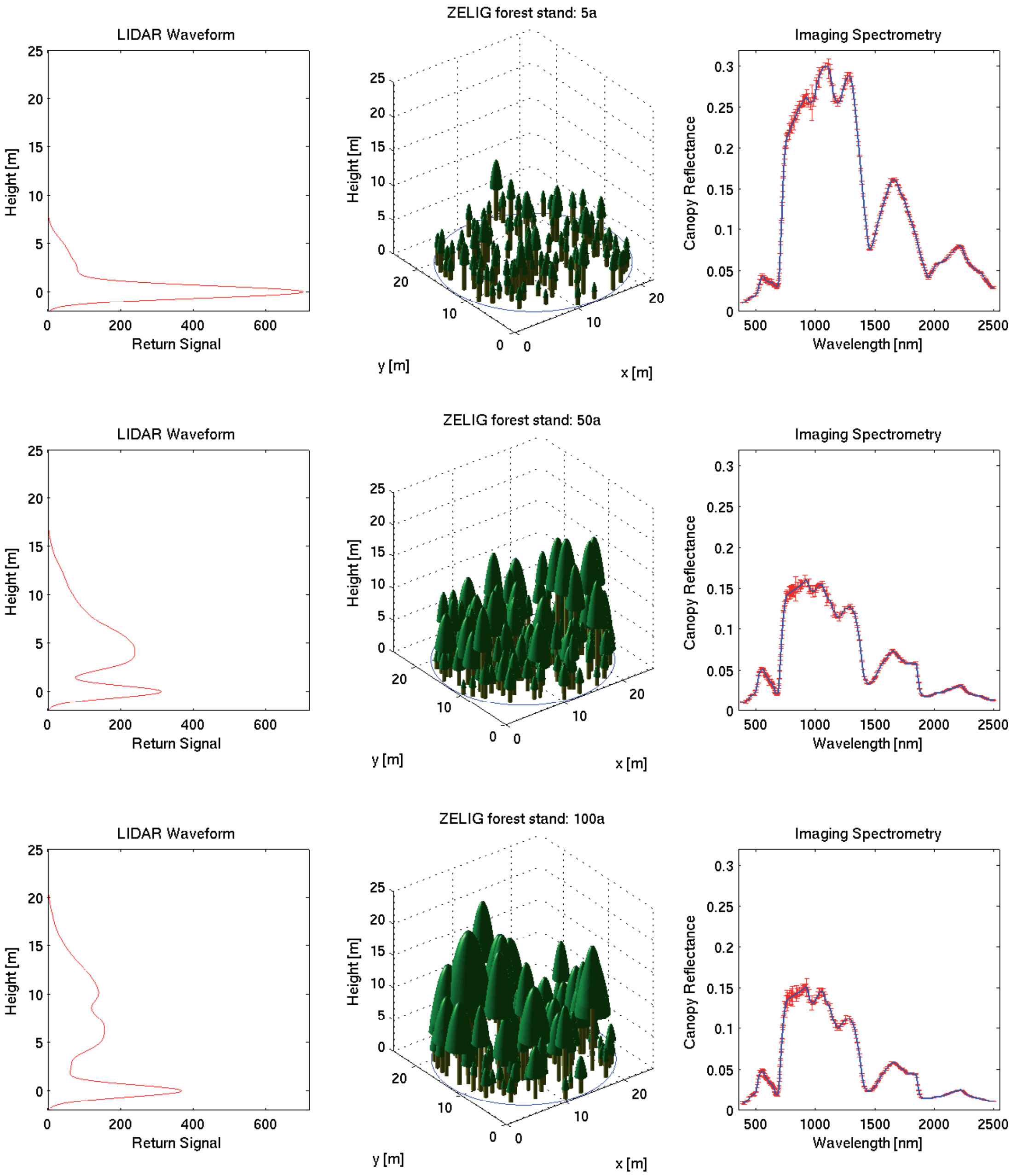


Figure 1. Simulated remote sensing signatures for the large footprint LIDAR LVIS (Blair et al. 1999) and the imaging spectrometer APEX (Nieke et al. 2004) (measurement uncertainties indicated by red error bars) over forest stands generated by the forest growth model ZELIG (stand ages: 5, 50, 100 years, soil type ADAMS)

Furthermore, typical measurement errors of the remote sensing data and uncertainties related to the radiative transfer models were as far as possible taken into account.
The synthetic data set avoids limitations due to the quantity, variability and accuracy of field sampling as well as the co-registration errors between field data and remote sensing observations. The ZELIG data set used here has already served well for similar studies of model simulation and data analyses (Kimes et al. 1997; Ranson et al. 1997).

## Forest growth modeling: ZELIG simulations

A version of the forest growth model, ZELIG developed by Urban (1990) and modified by (Weishampel et al. 1999), was used to simulate the dynamics of the southern boreal/northern hardwood forest transition zone found at the International Paper's Northern Experimental Forests (NEF) site located near Howland, Maine USA (45 $^o$ 12'N, 68 $^o$ 45'W). The model simulates the annual growth of each tree in a plot whose areal extent relates to the "gap" that is formed when a typical canopy dominant tree dies. The growth behavior of a species under ideal conditions (e.g., optimal temperature, soil moisture, light and nutrient availability) is estimated from silvicultural records available at each site. To implement the ZELIG model, site parameters, such as soil fertility and monthly values of temperature and precipitation, autecological parameters, tree height and diameter maxima as well as growth tolerances, were derived from empirical data and published sources. The implementation of the forest model ZELIG is described in greater detail in Ranson et al. (1997).
The ZELIG simulations were performed for ten different soil types over a time range of 250 years. Model results were recorded at 5-year intervals up to 100 years and at 25-year intervals up to 250 years. Soil types were used to provide a range of soil drainage conditions important for controlling forest growth and development in northern forests. More detailed information regarding soil types and characteristics was reported by (Ranson et al. 2001). A number of 15 separate runs were performed for each soil type. Stochastic changes in tree mortality, regeneration and weather conditions integrated in ZELIG generated thus a range of stand responses. Furthermore, the drainage conditions typical for the different soil types caused a high diversity in forest structure observed in the resulting data set. For each simulated stand and time step total woody biomass, number of trees, LAI as well as for every tree absolute height, diameter at breast height (DBH) and species were recorded (Tab. 1). The spatial resolution of the ZELIG simulations was set to an area of 30m x 30m corresponding to the scale of the employed remote sensing data.

Table 1. Parameter ranges describing the generation of the synthetic data set as well as the LUT for the subsequent RTM inversion. Additional parameters were fixed to model default or field measurement values: GeoSAIL parameterization: wood fraction = 0.09%, crown height width ratio = 7.8, crown shape = cone, spectral properties of woody canopy elements and understory; Waveform model parameterization: foliage reflectance (λ: 1560 nm) = 0.215, background reflectance (λ: 1560 nm) = 0.152, crown shape: hemi-ellipsoid, G-factor= 0.5, tree number = 60 (for the LUT generation)

| | **Variable** | **Units** | **Synthetic data set** | | **LUT** | |
|---|---|---|---|---|---|---|
| | | | **Min.** | **Max.** | **Min.** | **Max.** |
| Cab | Foliage chlorophyll content | $\mu g/cm^{-2}$ | 35 | 80 | 35 | 80 |
| Cw | Foliage water content | $mg/cm^{-2}$ | 0.025 | 0.065 | 0.025 | 0.065 |
| Cdry | Foliage dry matter | $mg/cm^{-2}$ | 0.02 | 0.05 | 0.02 | 0.05 |
| LAI | Leaf area index | - | 0.25 | 8.7 | 0.25 | 9 |
| fcover | Fractional cover[a] | % | 0.08 | 0.82 | 0.08 | 0.95 |
| Tree_z | Max. tree height | m | 4.7 | 29.6 | 4 | 30 |
| C_ext | Vert. crown exten.[a] | m | 3.7 | 28.6 | 3.4 | 28.7 |

a. No direct model input parameter but calculated for each canopy realization.

A total of 3900 forest stand simulations (10 soil types x 15 replications x 26 time steps) performed by ZELIG provided the structural canopy attributes for the subsequent parameterization of the radiative transfer models.

### Remote sensing signatures

Two radiative transfer models were used to generate the remote sensing signatures of the simulated forest stands as observed by two sensors, an imaging spectrometer and a large footprint LIDAR. The radiative transfer models, GeoSAIL and the LIDAR waveform model, were parameterized with the structural canopy attributes produced by the forest growth model ZELIG. As the majority of simulated forest stands was dominated by coniferous species, homogenous conifer stands were assumed for the RTM parameterization.

#### *Spectral canopy reflectance*

The coupled radiative transfer models PROSPECT and GeoSAIL described the spectral canopy reflectance $\rho(\lambda)$ as a function of foliage properties, canopy structure and instrument specifications. The canopy reflectance was simulated as observed from nadir in 299 spectral bands corresponding to the specification of the planned imaging spectrometer APEX (Tab. 2) (Nieke et al. 2004). APEX (Airborne Prism EXperiment), initiated under the ESA PRODEX program, is an airborne dispersive pushbroom imaging spectrometer operating in the spectral range between 380 - 2500 nm. The illumination conditions were defined by a sun angle set to 45° and a diffuse radiation fraction of 15%.

The input parameters as required by PROSPECT were assumed within typical ranges for conifers and randomly distributed, since the forest growth model does not provide information on foliage biochemistry (Table 1, see Kötz et al. 2004 for details). The canopy structure parameters of the RTM, leaf area index (LAI) and fractional cover (fcover), were described by the stand attributes generated by the ZELIG simulations. The average inclination angle was parameterized separately for green and woody canopy elements in GeoSAIL; spherical distribution was assumed for green, and plagiophile distribution for woody elements. The wood fraction and the crown height width ratio were set to values observed for the coniferous specie western hemlock (*Tsuga heterophylla*), (Huemmrich 2001). The spectral properties of the background and woody canopy elements were characterized by ground spectroradiometric measurements within a coniferous forest as described in Kötz et al. 2004.

Within the radiative transfer representation of GeoSAIL, several assumptions such as omitting mutual shading and tree overlapping have been made. In order to take into account uncertainties related to model assumptions, a Gaussian noise of 15% was added respectively to the LAI and fcover values provided by ZELIG. The magnitude of model uncertainty was oriented relatively to observations made by (Wang et al. 2001)

Finally, radiometric noise was added to the simulated canopy reflectance to account for measurement uncertainties resulting from several error sources associated to the imaging spectrometer performance and the radiometric correction. The relative instrument noise was characterized according to the specified signal to noise ratio performance of APEX at medium radiance level (APEX wikispace). The radiometric calibration of the imaging spectrometer was assumed to reach an absolute accuracy of 3%. The error related to the inaccuracy of the atmospheric correction was assumed to result primarily from aerosol optical thickness uncertainties, and was therefore spectrally dependant. A 2% maximal error was assumed in the first band (385 nm). The error was propagated to the remaining wavelengths according to a $\lambda^{-1.3}$ law which is typical for continental aerosols (Richter and

Schläpfer 2002). Standard error propagation, combining the above single error sources, was applied to generate simulated but nevertheless authentic canopy reflectance.

Table 2. Specification of the planned imaging spectrometer APEX (Nieke et al., 2004)

| Parameter | Unit | Value |
|---|---|---|
| Field of View | deg | 14 |
| Instantaneous Field of View | mrad | 0.48 |
| Spectral Channels | - | VNIR<=312 SWIR<=199 |
| Spectral Range | nm | 380 - 2500 |
| Spectral Sampling Interval | nm | <5 (380-1050nm) <10 (1050-2500nm) |
| Spectral Sampling Width | - | < 1.5 * Spectral Sampling Interval |
| Scanning Mechanism | - | Pushbroom |
| Dynamic Range | bit | 16 |

### *LIDAR waveform*

The above-described LIDAR waveform model generated the full LIDAR waveform signature over the simulated forest stands considering the specification of the large footprint LIDAR LVIS. The Laser Vegetation Imaging Sensor (LVIS) is an airborne, wide-swath mapping system developed at NASA's Goddard Space Flight Center capable of recording the full waveform over 25 meter diameter footprints table 3 (Blair et al. 1999).

The parameterization of the LIDAR waveform model was based on the structural attributes generated from the forest growth model ZELIG. The forest growth model provided a comprehensive description of the simulated forest stands required by the waveform model, including number of trees within a stand, tree height, DBH and LAI. Although tree height was available from the ZELIG output, it was calculated from tree DBH and allometric relationships developed from field measurements (Ranson et al. 1997; Sun and Ranson 2000). Crown geometry, defined by crown length and width, was subsequently calculated as function of tree height (Sun and Ranson 2000). Trees were randomly positioned within the simulated forest stands. The foliage and background reflectance were provided by spectrometric measurements and the crown shape was approximated as a hemi-ellipsoid. The G-factor was set to the value of 0.5 representing a spherical foliage distribution typical for conifers. For the sake of simplicity the underlying terrain was assumed to be flat.

As an additional parameter the vertical crown extension within each forest stand was calculated as the difference between the maximal tree height and the lowest crown base. Uncertainties related to errors associated to this sensor and data processing could not be taken into account because of their insufficient characterization.

Table 3. Instrument Specifications for LVIS waveform emulation, adapted from (Blair and Hofton 1999)

| Parameter | unit | value |
|---|---|---|
| Footprint | m | 25 |
| Along-beam laser intensity half-width ($\sigma_p$) | m | 0.6893 |
| Across-beam laser intensity half-width ($\sigma_f$) | m | 6.25 |
| Bin width | m | 0.1 |
| Gaussian kernel half-width ($\sigma$) | m | 0.6893 |

## Methods: RTM Inversion based on Look Up Tables (LUT)

The inversion of the two introduced radiative transfer models for the synergistic vegetation parameter estimation from LIDAR and imaging spectrometer data is based on a LUT approach. This is a conceptually very simple and efficient approach, which overcomes computational limitations as well as potentially the risk of local minimum convergence (Combal et al. 2002; Kimes et al. 2000). The approach also allows, due to its simplicity, the construction of a LUT comprising different remote sensing signatures of multiple sensors. Such a combined LUT is made possible by an interface between the two radiative transfer models. Common RTM parameters describing the canopy structure such as fractional cover, LAI and crown geometry establish a common forest stand parameterization used by each of the two models to generate a combined spectral and waveform signature of the respective canopy realization.

The LUT inversion approach can be split into two parts: (i) the generation of the LUT itself, and (ii) the selection of the LUT solutions corresponding to a given measurement. The selection of the LUT solutions followed a sequential approach.

### Generation of the LUT

The first step in generating a LUT was to sample the space of the input parameters of the two involved radiative transfer models ($LUT_P$). A total of 100,000 canopy realizations had been generated following a uniform distribution and specific ranges for the respective canopy parameter (Tab. 1). Then, the two RTM, linked by common vegetation parameters (fcover, LAI), were used to simulate the corresponding remote sensing signature table ($LUT_S$) for each canopy realization. The spectral properties of the background were also shared by both of the model parameterizations.

The parameterizations of the RTM for the LUT generation were in general defined accordingly to two previous experiments performed over a coniferous canopy, where each RTM was inverted separately (Koetz et al. 2006; Kötz et al. 2004). The LUT ranges were adapted to accommodate the conditions of the synthetic data set generated by ZELIG (Tab. 1). Note that the generation of the $LUT_P$ allowed the definition of some *a priori* information on the respective variable by constraining it to vary within limited ranges.

The parameterization of the LIDAR waveform model was modified in two major ways to improve the inversion performance relative to the study presented by Koetz et al. 2006. As already shown by the previous study and confirmed by inversion trials based on the ZELIG data set, the LAI estimations proved not to be stable. Strong correlation between the two canopy variables describing the canopy density, fcover and LAI, caused the LAI retrievals to deteriorate. The LAI was consequently fixed within the waveform model parameterization to a value of two, corresponding to an LAI of a well-developed canopy. A sensitivity study also showed a low sensitivity of the model simulations for variation of the LAI within the range of 1.5-3.5. Furthermore, the experience with the ZELIG data set showed a common occurrence of a more complex vertical structure within the canopy than has been considered up to now for the LUT parameterization. The canopies of the ZELIG generated forest stands often exhibited a crown layer separated into two pronounced strata (e.g. Figure 1). The tree height distribution of a forest stand parameterization was thus adapted for the LUT generation to mimic this behavior. Tree height distribution was now allowed to generate two strata, which could either overlap to one single stratum or form two vertically separated strata.

The measurement configurations used to generate the remote sensing signatures of $LUT_S$ considered the respective instrument specifications of the imaging spectrometer APEX and the large footprint LIDAR LVIS.

### Selection of the solution

The selection of the solution within the LUT was achieved by a sequential approach consisting of two steps. The LIDAR waveform information was exploited in a first step delivering information on the vertical and horizontal canopy structure. Part of this information was used as prior information within the subsequent second step, the exploitation of spectral information. The coupling of the waveform and spectral information was based on the assumption that the LIDAR provided the most reliable estimates of fcover, due to its direct measurement principle of canopy structure.

### *Exploiting waveform information: definition of prior information*

The solution of the waveform RTM inversion was found by minimizing the merit function ($\chi^2_{wave}$), defined as the simple squared-sum of distances between the reference waveform ($\omega_{ref}$) acquired by the LIDAR system and the simulated waveform ($\omega_{sim}$) found in the LUT (Eq. 1).

$$\chi^2_{wave} = \sum_{i=1}^{n_{bin}} \left(\omega^i_{ref} - \omega^i_{sim}\right)^2 \qquad (1)$$

where $n_{bin}$ is the number of bins of the digitized waveform.

However, given the ill-posed nature of a model inversion caused by measurement and model uncertainties, model inversion generally leads to a range of equally possible solutions (Combal et al. 2003). Thus, the LUT was first pre-selected following information provided by a direct assessment of the possible maximal tree height (Ni-Meister 2005). Maximal tree height was assumed to be within ± 10 % of a height, where the waveform signal initially increased a noise threshold (Drake et al. 2002a). Furthermore, the pre-selected LUT was sorted accordingly to the merit function ($\chi^2_{wave}$) and the first ten canopy realizations (those with the minimal $\chi^2_{wave}$) were considered as possible solutions. The median of the possible solutions defined the final solution and their standard deviation the uncertainty of the inversion (Koetz et al. 2006).

### *Exploiting combined spectral and waveform information*

The inversion of the GeoSAIL model was similarly solved as in the previous step by minimizing a simple distance criterion but was additionally restricted by prior information provided by the waveform RTM.

The spectral information was exploited by sorting the LUT according to the merit function $\chi^2_{rad}$. The spectral merit function was defined by the simple squared-sum of normalized differences between the reference reflectance $\rho_{ref}$ and the simulated reflectance $\rho_{sim}$ found in the $LUT_S$ (Eq. 2).

$$\chi^2_{rad} = \sum_{\lambda=1}^{n_\lambda} \left( \frac{\rho^\lambda_{ref} - \rho^\lambda_{sim}}{\rho^\lambda_{ref}} \right)^2 \qquad (2)$$

where $n_\lambda$ is the number of bands of the spectrum recorded by the imaging spectrometer APEX.

The LIDAR waveform information was introduced to the retrieval process by restricting the LUT based on prior information of the canopy variable fcover. LUT entries have been constrained by the following criterion:

$$f\,cover = f\,cover_\omega \pm \Delta f\,cover_\omega \qquad (3)$$

where $fcover_\omega$ represents the fractional cover as derived from the waveform information and $\Delta fcover_\omega$ its uncertainty related to the waveform model inversion. This simple way of introducing prior information to the inverse problem was made possible by the plain nature and the combined structure of the employed LUT approach.

Finally the possible solutions considered were those that were within 20% of the best spectral match and considering the prior information on the fcover. The 20% threshold was derived after test and error trials and is consistent with findings proposed in earlier studies (Combal et al. 2002; Kötz et al. 2004). The median of possible solutions was considered as final solution and their standard deviation as the uncertainty of the model inversion.

## Results and discussion: Evaluation of RTM coupling strategy

The synthetic data set generated by the forest growth model ZELIG was used to evaluate the performance of the proposed method for a wide range of forest stands. First, the retrieval performance based solely on the information dimension provided by the LIDAR sensor was addressed separately. The improvement of the combined spectral and waveform information dimensions was subsequently evaluated relative to the spectral information performance. The simple root mean square error (RMSE) was calculated to quantify the agreement between the respective reference and estimated parameter values. The correlation coefficient ($R^2$) of a linear regression was also presented. The results of the site over the soil type ADAMS, presented in the figures 2-3, are discussed in more detail. The overall performance of the proposed RTM inversion approach and its transfer to all of the considered soil types are presented in the table 4. The results are grouped in table 4 by soil type for convenience. Adams and Dixfield represent well drained soils while Kinsman, Peachman, Scantic and Westbury are considered poorly or very poorly drained. The remaining soils are of intermediate drainage class.

Table 4. Retrieval performances for the respective canopy parameters based on the LIDAR waveform information and based on the combined spectral and waveform information. Overall performance as well as separate performaces for ten different soil types are quantified as RMSE and $R^2$ between reference and estimated parameters.

| | LIDAR | | | | | | Combined Imaging Spectroscopy / LIDAR | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Tree_z [m] | | C_ext [m] | | Fcover [%] | | LAI [ ] | | Fcover [%] | | Cab [µg/cm²] | | Cw [mg/cm²] | |
| Soil Types | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE |
| ADAMS | 0.95 | 1.74 | 0.94 | 1.61 | 0.92 | 0.08 | 0.68 | 1.23 | 0.84 | 0.07 | 0.86 | 5.06 | 0.79 | 0.0053 |
| BOOTHBAY | 0.99 | 0.50 | 0.97 | 1.69 | 0.92 | 0.08 | 0.84 | 1.10 | 0.93 | 0.06 | 0.74 | 6.95 | 0.66 | 0.0068 |
| COLONEL | 0.93 | 1.76 | 0.92 | 2.03 | 0.92 | 0.09 | 0.71 | 1.25 | 0.85 | 0.07 | 0.82 | 5.63 | 0.83 | 0.0048 |
| CROGHAN | 0.94 | 1.74 | 0.94 | 2.01 | 0.91 | 0.09 | 0.70 | 1.27 | 0.84 | 0.07 | 0.83 | 5.38 | 0.78 | 0.0052 |
| DIXFIELD | 0.94 | 1.59 | 0.92 | 1.78 | 0.92 | 0.09 | 0.60 | 1.42 | 0.86 | 0.07 | 0.79 | 6.07 | 0.78 | 0.0058 |
| KINSMAN | 0.95 | 1.67 | 0.96 | 1.53 | 0.91 | 0.07 | 0.74 | 1.06 | 0.85 | 0.07 | 0.84 | 5.21 | 0.82 | 0.0051 |
| MARLOW | 0.95 | 1.75 | 0.95 | 1.37 | 0.93 | 0.08 | 0.73 | 1.13 | 0.87 | 0.07 | 0.85 | 5.30 | 0.79 | 0.0056 |
| PEACHAM | 0.98 | 1.10 | 0.96 | 1.55 | 0.91 | 0.07 | 0.86 | 0.91 | 0.92 | 0.06 | 0.76 | 6.37 | 0.69 | 0.0067 |
| SCANTIC | 0.99 | 0.49 | 0.98 | 1.31 | 0.92 | 0.07 | 0.88 | 0.88 | 0.93 | 0.06 | 0.75 | 6.66 | 0.65 | 0.0070 |
| WESTBURY | 0.96 | 1.47 | 0.95 | 2.16 | 0.90 | 0.08 | 0.79 | 1.11 | 0.87 | 0.07 | 0.79 | 6.20 | 0.80 | 0.0054 |
| OVERALL | 0.97 | 1.46 | 0.97 | 1.72 | 0.92 | 0.08 | 0.80 | 1.15 | 0.90 | 0.07 | 0.80 | 5.92 | 0.76 | 0.0058 |

The inversion of the waveform RTM provided reliable estimates of model parameters describing the vertical as well as the horizontal canopy structure. The parameters were all retrieved with high correlation coefficients and low RMSE (Fig. 2, Tab. 4) two parameters describing the vertical canopy structure, maximal tree height and the vertical crown extension, showed similar performances. Both parameters were slightly underestimated which was most likely caused by missing the signal start of the highest tree top. Due to the nature of the employed merit function, low signals, as recorded from single tree tops extending over the canopy, received a relative low weight within the retrieval algorithm. The comparable values of the vertical crown extension relative to the maximal tree height also indicated that the observed forest stands exhibited a rather continuous vertical distribution of crowns. The examples of ZELIG generated forest stands presented in figure 1 suggested such a vertical canopy structure. The horizontal structure represented by the canopy fractional cover showed some underestimation for low values as well as an overestimation for high values. Some of this behavior could be attributed to compensation for the fixed LAI parameter, which probably assumed a relative high crown density for sparse, younger stands and a relative low crown density for closed, mature stands. Nevertheless, this assumption was necessary for a stable inversion performance due to a strong inter-correlation between LAI and fcover. Finally, the overall high performance of the waveform model inversion has been only achieved by the implementation of a two strata canopy and a highly variable vertical tree height distribution into the LUT generation.

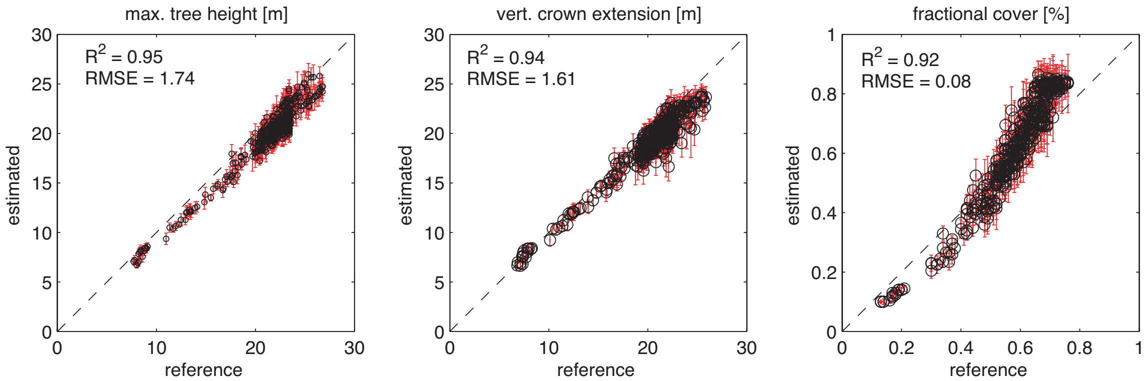


Figure 2. Vegetation parameter estimates describing the vertical and horizontal canopy structure retrieved by the inversion of the LIDAR waveform RTM. Results describe forest stands generated by ZELIG over the soil type ADAMS (n=390 forest stands). Error bars represent the uncertainty of the model inversion.

The combined RTM inversion performed well retrieving estimates of biophysical, LAI and fcover, and biochemical parameters, foliage content of chlorophyll and water, with significant correlation coefficients and low RMSE (Fig. 3b, Tab. 4). All parameters show linear relationships close to the 1:1 line. Only the LAI exhibits a significant scattering above an LAI value of five, consistent with the known saturation effect for this parameter in closed canopies. The introduction of prior information on the fcover parameter, derived from the waveform information content, clearly improved the retrieval performance relative to estimates based only on spectral information. The fcover estimates based on the combined RTM inversion resulted in a 22.2% (24.4%) lower RMSE and a 17% (15.4 %) increase in terms of $R^2$, calculated over the stands of the ADAMS site (the total of all sites). The results for the soil type ADAMS, presented in figure 3, also indicated that most of the improvement was caused by the reduction of scattering for fcover greater than 0.5. The uncertainties of the RTM inversion for low fcover values have been also reduced. Relative to the fcover estimates based solely on waveform information content the combined retrieval showed a more linear relationship causing an even lower RMSE. However, retrieval performance of the remaining parameters, especially the biochemistry, decreased by the introduction of prior information on the fcover. This had a number of different causes. First, the prior information on the fcover considerably reduced the number of available LUT entries, which consequently resulted in a lower probability to find a solution fitting the information content related to the biochemistry. Further, the prior information mostly improved the retrieval for closed canopies where estimation of foliage biochemistry is generally least affected by canopy structure (Zarco-Tejada et al. 2001). Also the RTM GeoSAIL does not incorporate certain effects of canopy structure affecting the biochemistry estimation, such as mutual shading. Consequently, improvement of biochemistry retrievals by introduction of prior information on fcover was limited for this data set. Finally, the RTM inversion on the spectral information already provided good results since prior information on all parameters was introduced implicitly during the LUT generation and the synthetic data set assumed ideal measurement conditions. Nevertheless, in reality due to the important effect of the canopy architecture an improved characterization of the canopy structure by prior information should also enhance the capability to retrieve biochemistry from imaging spectroscopy (Asner 1998; Dawson et al. 1999; Gastellu-Etchegorry and Bruniquel-Pinel 2001).

The performance of the combined RTM inversion discussed above in more detail for the soil type ADAMS performed similar for the nine remaining soil types with different ecological conditions (Tab. 4). In spite of the changing soil types and the consequently differently evolving canopy structure, the retrieval remained stable and thus transferable among the sites. However, assumptions made for the generation of the synthetic data set, such as the constant background reflectance and a flat terrain, still limit the universality of the results.

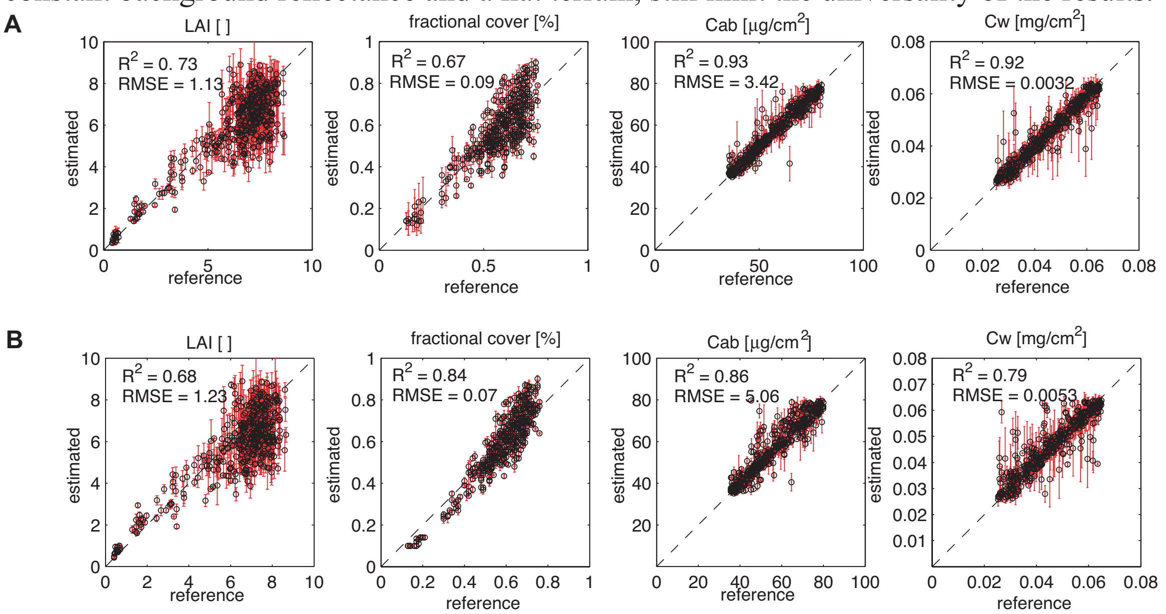


Figure 3. Estimates of biophysical and biochemical parameters retrieved based solely on the spectral information content (Fig. 3a) as well as on the coupled RTM inversion (Fig. 3b). Results describe forest stands generated by ZELIG over the soil type ADAMS (n=390 forest stands). Error bars represent the uncertainty of the model inversion.

## Conclusions

Remote sensing of vegetation properties has been shown to be a generally ill-posed problem, partly due to the available indirect detection methods and measurement uncertainties but also due to the limited representation of the involved processes in the retrieval. This includes the inversion of RTM, because even physically based radiative transfer models have to be partly based on assumptions and parameterizations in order to be invertible. Consequently the introduction of prior or ancillary information into the retrieval process is a necessary and useful approach to increase the robustness of canopy parameter estimation by remote sensing. One promising way of deriving prior information is to exploit independent information dimensions provided by multiple sensors.

The presented study showed the potential for the combined information exploitation of multiple sensors based on physically based radiative transfer modeling. The two information dimensions provided by imaging spectrometry and LIDAR were successfully used to derive a comprehensive canopy characterization, relevant for the assessment of biomass, productivity of vegetation and risk of natural hazards such as forest fires (Chuvieco 2003; Sellers et al. 1997). The specific information content, inherent to the observations of the respective sensors, was able to complement the canopy characterization but also helped to stabilize the RTM inversion. Prior information derived from LIDAR observations helped to improve the retrieval performance of the canopy structure, which is in general only indirectly and thus with relative high uncertainties inferable from pure spectral information. The results of the study provided robust estimates of the vertical and horizontal canopy structure as well as biophysical and –chemical canopy parameters for a wide range of forest stands. The major limitation of the results was its validation relative to a synthetic data set. However, the generation of the data set by an ecologically sound forest growth model linked to physically based RTM ensured the reproduction of most processes important in reality. The advantage of a synthetic data set on the other hand is the wide range of forest stands conditions covered and avoiding limitations related to measurement errors. The explicit description of the canopy structure by the forest growth model also allowed for an increased understanding of the processes impacting the LIDAR waveform signal and thus led to an improved retrieval algorithm.

Although these findings are based on a synthetic data set, they bear a high significance for future space-borne Earth-Observation platforms with multiple sensors such as the proposed mission Carbon-3D, which is supposed to provide global biomass estimates based on similar observation techniques (Hese et al. 2005). The simultaneous assessment of horizontal and vertical structure, described by fcover, LAI and tree height as provided by the proposed approach, would most certainly improve the estimates of the sought variable biomass. Further, due to the simplicity and the generic nature of the coupled RTM strategy the approach could be easily extended to further information dimensions, such as provided by multiangular or microwave observations (Diner et al. 2005; Disney et al. 2006; Verstraete et al. 1996). The spatial discontinuous samples of spaceborne LIDAR observations could be also interpolated by multiangular and spectral earth observations to obtain a spatial continuous coverage of vertical forest canopy structure (Kimes et al. 2006).

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# PART C: SYNOPSIS

## Main findings and progress

The independent information dimensions provided by the two Earth Observation systems imaging spectrometry and LIDAR have been identified to be complementary for a comprehensive characterization of a heterogeneous canopy. Further, physically based radiative transfer modeling has been stated as an appropriate approach for the explicit description of the relationship between the remote sensing signal and the observed target, in this case the vegetation canopy. The presented dissertation addressed the estimation of biophysical and biochemical vegetation canopy properties from the combined Earth Observation signature of imaging spectrometry and LIDAR based on appropriate radiative transfer models. The objectives of the dissertation led to a number of research questions listed in the section describing the scientific setting. In the following these research questions will be addressed and discussed in the context of the results and findings presented in the journal papers included in the publication section (indicated as e.g. Kötz et al., 2004, *first publication*) as well as additional contributions.

A prerequisite for the successful application of radiative transfer modeling is the selection of an appropriate Radiative Transfer Model (RTM) depending on the observed target. For the case of imaging spectroscopy over heterogeneous canopies a number of RTM forward simulations were performed (Kötz et al., 2003b; Kötz et al., 2004, *first publication*). The forward simulations demonstrated the viability of two chosen canopy reflectance models in terms of their radiative transfer representation within a heterogeneous canopy. Key parameters governing the radiative transfer within a forest were also identified and assessed by forward simulation at different spatial scales (Kötz et al., 2003a). A comprehensive canopy parameterization of the complex 3-D RTM FLIGHT (North, 1996) based on a extensive field campaign enabled a comparison of simulated canopy reflectance with the actual signal acquired by imaging spectrometry over a coniferous canopy. The FLIGHT model is considered as one of several reference models within the Radiation Transfer Model Intercomparison (RAMI) and, thus, has been extensively tested and validated (Pinty et al., 2001; Pinty et al., 2004). The effect of uncertainties, related to canopy parameterization and model implementation, on the simulated canopy reflectance was considered using standard error propagation. The resulting forward simulations of canopy reflectance for four well characterized test sites showed the capability of FLIGHT to scale-up canopy variables from the foliage to the canopy level. The RTM simulations characterized the canopy reflectance as observed by an imaging spectrometer within model and measurement uncertainties (Kötz et al., 2003b). Following the same canopy parameterization, forward simulations of the canopy reflectance with the relative simple RTM GeoSAIL (Huemmrich, 2001) were performed and its performance compared to the one of FLIGHT. Despite the different nature of the two RTM and their significant different levels of complexity to represent the canopy structure, they performed comparably (Kötz et al., 2004, *first publication*). A second forward modeling study assessed the influence of canopy heterogeneity and structure at different spatial scales. High resolution imaging spectrometer with a spatial resolution of one meter supported by LIDAR data allowed separating the complex forest scene into its scene components such as crown, canopy gap and shadows. The results pointed out the strong influence of shading caused by the heterogeneity and tree geometry within a coniferous forest. The canopy structure was consequently identified as being one of the key parameters governing the reflectance of heterogeneous canopies (Kötz et al., 2003a).

The similar model performance in their forward mode allowed to invert the relative simple model GeoSAIL instead of the complex ray-tracing RTM, FLIGHT, which significantly reduced the computational cost of the model inversion. However, due to the simplified representation of the canopy structure in GeoSAIL, the effect of mutual shading of crowns is neglected in its radiative transfer characterization. In the parameterization of the RTM the spectral properties of the background have been assumed to remain spatially constant. While valid for the presented regional application, this assumption is a major limitation when applied on a broader range, because the spectral properties of the background can vary with space and time (Huemmrich & Goward, 1997; Song et al., 2002; Koetz et al., 2005a). Considering these assumptions the results of the model inversion verified the invertability of the coupled RTM PROSPECT (Jacquemoud & Baret, 1990) and GeoSAIL. The resulting findings clearly showed the potential of radiative transfer modeling to quantitatively assess vegetation canopy properties of a heterogeneous canopy (Kötz et al., 2004, *first publication*). The Look-Up Table (LUT) approach chosen for the RTM inversion allowed for the implementation of general prior information depending on the vegetation type, which improved the achieved retrieval performance. The canopy parameters LAI, fractional cover, foliage water and dry matter content were successfully retrieved from imaging spectrometer data taken over the Swiss National Park in their actual spatial distribution. The quantitative assessment of such biophysical and biochemical parameters based on imaging spectroscopy and their relevance for regional to global ecosystem modeling have been discussed in (Schaepman et al., 2004).

Both small and large footprint LIDAR systems have recently found as being particularly sensitive to canopy structure of heterogeneous canopies due to their direct measurement principle of the distribution of canopy elements in space (Lefsky et al., 2002). Two studies in the Swiss National Park based on small footprint LIDAR data successfully showed the estimation of location and geometric properties of single trees as well as of fractional cover and LAI describing the canopy structure (Morsdorf et al., 2004; Morsdorf et al., 2006 (accepted)). Despite its lower horizontal resolution, the advantage of large footprint LIDAR is its capability to provide observations from spaceborne platforms (e.g. GLAS on ICESat). Therefore, data sets at global scale can be acquired by large footprint LIDAR on an operational basis. Several RTM for large footprint LIDAR have been developed, that incorporate an appropriate forest canopy representation, sensor specifications and the involved physical processes describing the radiative transfer in the canopy. The inversion of such a physically based model (Sun & Ranson, 2000), describing the waveform recorded by a large footprint LIDAR system, presents a novel concept for retrieving biophysical parameters in a robust and quantitative manner. The invertibility and potential of the waveform RTM for the retrieval of forest structure parameters has been successfully validated on a synthetic data and an actual data set generated from small footprint LIDAR returns (Koetz et al., 2006, *second publication*). Horizontal and vertical forest structure expressed as fractional cover, maximum tree height and vertical crown extension could be estimated using an inversion algorithm based on a LUT approach. However, the LAI retrieval of the forest canopy showed fundamental difficulties. Several assumptions were made in the parameterization in order to achieve a successful model inversion. The foliage and background reflectance were set to field based spectrometric measurements. Further, the crown shape, the mean foliage projection factor and the number of trees were assumed to be known and kept constant. Nevertheless, imaging spectroscopy can provide spectral information on the relevant canopy components and can help to define the crown shape and foliage projection factor by detecting the observed forest type. Imaging spectroscopy would thus be able to reduce the uncertainties caused by the above assumptions. A remaining issue of the general interpretation of large footprint LIDAR is caused by the effect of varying terrain within the footprint, which has been neglected in the presented study.

As presented in the above sections both information dimensions provided by imaging spectrometry and LIDAR can be exploited independently for the retrieval of forest parameters using physically based radiative transfer models. However, the retrieval of vegetation characteristics through RTM inversion should be improved by increasing the number of independent information sources (Verstraete et al., 1996). Observations made by imaging spectrometers and LIDAR represent such independent information sources that describe the spectral and the spatial information dimension over a vegetation surface. An initial study, based on forward simulations of the FLIGHT model, showed the use of an explicit forest stand representation characterizing the actual canopy structure, which was described by LIDAR derived single tree geometry (Koetz et al., 2003). Accuracy and uncertainties of the simulated canopy reflectance using the explicit stand representation were superior to simulations based on model parameterization with mean parameter values. Supported by these initial findings an approach was developed to characterize forest canopies based on the combined remote sensing signal of imaging spectrometry and LIDAR. The inversion of the two linked models, GeoSAIL and the waveform LIDAR RTM, provided a methodology for synergistically exploiting the specific and independent information dimensions obtained by the two Earth Observation systems (Koetz et al., 2006 (submitted), *third publication*). The linkage of the two RTMs was based on the fact that the signals of both sensors are governed by the same basic physical processes involved in the radiative transfer. Consequently, an interface between the two RTMs, sharing the same physical concept and common input parameters, could be established. A common parameterization of the canopy structure was used by the above mentioned models to generate a combined spectral and LIDAR waveform signature of the simulated canopy. The combined simulated remote sensing signatures together with the respective canopy parameters populated a LUT, which was subsequently used for the RTM inversion. The inversion followed a sequential approach that at first exploited LIDAR observations for the retrieval of information on the canopy structure. The fractional cover retrieved from the LIDAR waveform information, was introduced as prior information to constrain and thus improve the RTM inversion based on the spectral information. The coupling scheme of the waveform and spectral information was based on the hypothesis that LIDAR observations provided the most reliable estimates of fractional cover, due to their direct measurement principle of the vertical canopy structure. The integration of the spectral and waveform information content into a combined retrieval algorithm was thus based on the plain nature and combined structure of the employed LUT approach. The performance of the proposed method was evaluated on a synthetic data set generated by the forest growth model ZELIG (Urban, 1990) providing a wide range of coniferous forests at different succession stages and multiple sites. The large variability of this data set led to an optimized LUT generation that allowed a more general representation of the canopy structure including forest stands with multiple strata. The performance of the combined RTM inversion delivered robust estimates on forest canopy characteristics ranging from maximal tree height, fractional cover, LAI to foliage chlorophyll and water content. Furthermore, the introduction of prior information on the canopy structure derived from LIDAR observations significantly improved the retrieval performance relative to estimates based solely on spectral information. The specific information content inherent to imaging spectrometry and LIDAR was thus not only able to complement the canopy characterization but also helped to stabilize the RTM inversion.

## Conclusions

This research was motivated by the increased information dimensionality provided by current and future Earth Observation systems measuring the complex and dynamic medium of the vegetated surface of the Earth. Advanced and reliable algorithms that fully exploit this enhanced Earth Observation information are needed to deliver consistent data sets of the Earth vegetation condition describing its spatial distribution and change over time.

The dissertation contributes to this challenge by developing a novel methodology for the combined exploitation of imaging spectrometer and LIDAR measurements based on radiative transfer modeling. The specific information content, inherent to the observations of imaging spectrometry and LIDAR, assesses different but complementary characteristics of the complex vegetation canopy. The combination of these two information dimensions offers a unique and reliable canopy characterization for monitoring of the Earth vegetation. The invertibility of two physically based models describing the radiative transfer relevant for each of the two Earth Observation systems showed the viability and feasibility of the chosen approach. The retrieval performances of the two RTM were assessed in separate case studies over a coniferous forest. The inversion of the two linked RTM realized subsequently the combined exploitation of the independent and specific information dimensions obtained by the two Earth Observation systems. The exploitation of the two independent information sources ensured a parameter retrieval of increased robustness, but also provided an enhanced canopy characterization including the horizontal and vertical canopy structure as well as the foliage biochemistry. A synthetic, but realistic data set generated using a forest growth model helped to validate the developed algorithm over forest stands of changing age and under different environmental conditions. The stable retrieval performance over the large ranges of the validation data set showed the potential of the linked RTM inversion to provide reliable and consistent data sets of quantitative vegetation properties.

These findings could thus be of significance for future spaceborne Earth Observation platforms with multiple sensors of similar observation capabilities, such as the proposed mission Carbon 3-D (Hese et al., 2005). Further, an enhanced vegetation characterization, including canopy height, LAI and foliage biochemistry being important ecosystem properties, will help to assess the human or natural induced change of land systems. As part of an integrated approach, which includes societal and natural processes and dynamics, Earth Observation of vegetation can consequently contribute to sustain important ecosystem services, such as agricultural productivity, clean air, potable water and mitigation of forest fire and floods (Ojima et al., 2005).

## Outlook

Future research within the addressed field should obviously concentrate on the extension of the synergistic exploitation of multi-sensor observations to include additional information dimensions provided by Earth Observation. Multiangular observations have been identified as being sensitive to forest structure and represent consequently an independent information source capable to further complement the proposed retrieval algorithm. The ESA mission CHRIS on Proba provides multiangular observations in unprecedented high spectral and spatial resolution. CHRIS observations are thus well suited to study the complementary content of the directional and spectral information dimension. An initial study already proposed an approach to assess canopy structure and heterogeneity based on the multiangular observations of the CHRIS sensor (Koetz et al., 2005b). Multiangular observations could also interpolate the spatial samples of spaceborne LIDAR observations to obtain a spatial continuous coverage of vertical canopy structure (Kimes et al., 2006). A further information source complementing the observations and thus the retrieval of heterogeneous canopy characteristics is the backscatter coefficient of imaging RADAR. The LIDAR waveform RTM used in this dissertation has been originally developed to describe the radiative transfer in the microwave wavelength domain (Sun & Ranson, 1995). The presented approach could thus be extended to include the Earth Observation measurements of RADAR systems.

The optimal exploitation of multiple information dimensions provided by multi-sensor platforms will require further improved retrieval algorithms, which will be able to identify the optimal set of information input and combine them in an efficient manner. The information input should include prior and ancillary information derived from in-situ measurement networks and ecological databases. Retrieval algorithms should also be focused on vegetation variables, which are controlling the radiative transfer within the canopy and can thus be directly related to Earth Observation measurements. Further interpretation of remote sensing data should also consider as much as possible the underlying physical and biological processes. This will consequently lead to a spatially enhanced and more detailed integration of Earth Observation data into land surface process models on a local to regional scale or into Earth system models on a global scale.

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# APPENDIX

## Acknowledgements

A major part of the research relevant for the presented dissertation has been conducted and partly funded within the European Community project ’Forest Fire Spread and Mitigation (SPREAD), EC-Contract Nr. EVGI-CT-2001-0027 and BBW-Contract Nr. 01.0138. The airborne operations of the acquisition of the imaging spectrometer data have been supported by the European Community Infrastructure project HYSENS under the guidance of DLR. The access and logistic necessary for the fieldwork have been granted by the Swiss National Park.

I greatly appreciate the willingness of Frédéric Baret (INRA, France) to review this thesis and contribute an external expertise of the work.

I would like to express my gratitude to everybody who contributed to the completion of this work – it definitely requires more than a single person to bring a dissertation to a successful end!

First of all I would like to thank the members of my dissertation committee who supervised and contributed in various ways to the dissertation. Klaus Itten, as my main supervisor, always motivated and supported my work in a very generous way. I can’t image a more fruitful environment and infrastructure as he has offered to me at the RSL. Britta Allgöwer initiated and inspired the work by providing the application background and always rising the right questions at the right moment. My team leader Mathias Kneubühler always kept my back clear of trouble and was very supportive in the day-to-day work of the thesis. Michael Schaepman first also as team leader and later from the distance was very helpful to focus the various tasks and to put the work into a strategic context.

A special thanks is due to my colleagues and friends at the Geographical Institute of the University of Zürich, Jason Brazil, Martin Beusch, Stephan Bojinski, Stephan Dangel, Othmar Frey, Stephan Gruber, Silvia Huber, Tobias Kellenberger, Erich Meier, Felix Morsdorf, Gabi Schaepman-Strub, Daniel Schläpfer and Jürg Schopfer, – without all the discussions, at work or after-hours, and support in fieldwork or otherwise the time would not have been so enjoyable and the dissertation after all not possible. I also enjoyed keeping the contact and collaborating with Frédéric Baret (INRA), Paul Bowyer (University of Salford), Joachim Hill (University of Trier) and part of his group Thomas Jarmer, Achim Röder and Martin Schlerf, Stefanie Holzwarth and the spectroscopy group (DLR), Patrick Hostert (Humboldt University), Marie Weiss (INRA), Jean-Luc Widlowsky (JRC), Nikolaus Zimmermann (WSL).

The research of the dissertation was partly inspired and based on a scientific visit to the Biospheric Sciences Branch at NASA GSFC. I’m indebted to Betsy Middelton, Petya Campbell and Jon Ranson for their support, which made this visit possible and a very fruitful personal and scientific experience. Specifically I would like to thank Gouqing Sun for his continuous scientific support and collaboration.

I much appreciated the development of many personal friendships during the eventful period of my academic education. I’m especially thankful to the continuous contact and close friendship with Björn, Fabian and Sebastian, which survived over quite a bit of time and space. I thank my parents, Inga and Ulrich, as well as my sister Roswitha and brother Thomas for their long lasting help and moral support, which finally brought me all the way to this point and I never took for granted. Finally, I would like to express my gratitude to Magdalena who gives me the necessary warmth without life wouldn’t be half as beautiful.

## Curriculum Vitae

**Benjamin Kötz**
Day and place of birth: 10.12.1974, Hamburg
Nationality: German

| | |
|---|---|
| **Secondary school**, Gymnasium Christianeum (Hamburg/Germany)<br>Abitur (German A-levels) | 1985<br>- 1994 |
| **Eureka Senior High School** (Eureka/USA)<br>Student exchange program, attendance of the Senior class (12 month) | 1992 |
| **Université de Caen** (Caen/France)<br>Attendance of classes of the French language (10 month) | 1994<br>- 1995 |
| **University of Trier** (Trier/Germany)<br>Master of science in Applied Environmental Sciences (included Remote sensing, Climatology, Botany, Geography)<br>Thesis on remote sensing for precision farming, part of the EC-project CROMA | 1995<br>- 2002 |
| **INRA** (Institut National de la Recherche Agronomique), (Avignon / France)<br>Internship as part of the EC LEONARDO exchange program (6 month)<br>Contracting in the EC-project CROMA (5 month) | 1999<br>&<br>2001 |
| **UNDCP** (United Nations Drug Control Program), (Vienna/Austria)<br>Internship with the Illicit Crop Monitoring Program (3 month) | 2000 |
| **University of Zürich** (Zürich/Switzerland)<br>PhD studies at the Remote Sensing Laboratories (RSL)<br>Thesis on Retrieval of biophysical and biochemical properties of heterogeneous canopies, part of the EC-project SPREAD | 2002<br>- 2006 |
| **NASA-GSFC** (NASA – Goddard Space Flight Center), (Washington DC/ USA)<br>Scientific visit to the Biospheric Sciences Branch (3 month) | 2004 |

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